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Revised stratigraphy of Neogene strata in the Cocinetas Basin, La Guajira, Colombia

F. Moreno · A. J. W. Hendy · L. Quiroz · N. Hoyos · D. S. Jones · V. Zapata · S. Zapata · G. A. Ballen · E. Cadena · A. L. Cárdenas · J. D. Carrillo-Briceño · J. D. Carrillo · D. Delgado-Sierra · J. Escobar · J. I. Martínez · C. Martínez · C. Montes · J. Moreno · N. Pérez · R. Sánchez · C. Suárez · M. C. Vallejo-Pareja · C. Jaramillo

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Abstract The Cocinetas Basin of Colombia provides a valuable window into the geological and paleontological history of northern South America during the Neogene. Two major findings provide new insights into the Neogene history of this Cocinetas Basin: (1) a formal re-description of the Jimol and Castilletes formations, including a revised contact; and (2) the description of a new lithostratigraphic unit, the Ware Formation (Late Pliocene). We conducted extensive fieldwork to develop a basin-scale stratigraphy, made exhaustive paleontological collections, and performed $^{87}Sr/^{86}Sr$ geochronology to document the transition from the fully marine environment of the Jimol Formation (ca. 17.9–16.7 Ma) to the fluvio-deltaic environment of the Castilletes (ca. 16.7–14.2 Ma) and Ware (ca. 3.5–2.8 Ma) formations. We also describe evidence for short-term periodic changes in depositional environments in the Jimol and Castilletes formations. The marine invertebrate fauna of the Jimol and Castilletes formations are among the richest yet recorded from Colombia during the Neogene. The Castilletes and Ware formations have also yielded diverse and biogeographically significant fossil vertebrate assemblages. The revised lithostratigraphy and

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F. Moreno · L. Quiroz · N. Hoyos · V. Zapata · S. Zapata · G. A. Ballen · E. Cadena · A. L. Cárdenas · J. D. Carrillo-Briceño · J. D. Carrillo · J. Escobar · C. Martínez · J. Moreno · N. Pérez · R. Sánchez · C. Suárez · M. C. Vallejo-Pareja · C. Jaramillo
Smithsonian Tropical Research Institute, Panamá, USA

F. Moreno · N. Hoyos · A. L. Cárdenas
Corporación Geológica ARES, Bogotá, Colombia

F. Moreno (✉)
University of Rochester, Rochester, NY, USA
e-mail: federicomrn@gmail.com

A. J. W. Hendy
Natural History Museum of Los Angeles County, Los Angeles, CA, USA

A. J. W. Hendy · D. S. Jones
Florida Museum of Natural History, Gainesville, FL, USA

L. Quiroz
University of Saskatchewan, Saskatoon, Canada

N. Hoyos · A. L. Cárdenas · J. Escobar
Universidad del Norte, Barranquilla, Colombia

V. Zapata
Ecopetrol S.A., Bogotá, Colombia

E. Cadena
Senckenberg Museum, Frankfurt, Germany

J. D. Carrillo-Briceño · J. D. Carrillo
Paleontological Institute and Museum, University of Zurich, Zurich, Switzerland

D. Delgado-Sierra · J. I. Martínez
Universidad Eafit, Medellín, Colombia

C. Martínez
Cornell University, Ithaca, NY, USA

C. Montes · N. Pérez
Universidad de los Andes, Bogotá, Colombia

J. Moreno
University of Nebraska-Lincoln, Lincoln, NE, USA

C. Suárez
Museo de la Plata, La Plata, Argentina

chronostratigraphy presented here provides the necessary background information to explore the complete evolutionary and biogeographic significance of the excellent fossil record of the Cocinetas Basin.

Keywords Stratigraphy · Paleontology · Paleoenvironments · GABI (Great American Biotic Interchange) · Miocene · Pliocene · Cocinetas Basin · La Guajira Peninsula · Colombia

Introduction

Cenozoic pull-apart sedimentary basins are common along the northern edge of the South American continent as a consequence of the interaction between the South American and Caribbean plates (Muessig 1984; Pindell 1991; Zapata et al. 2014). One such sedimentary basin is Cocinetas, which is located on the eastern flank of La Guajira Peninsula, northern Colombia (Fig. 1). The Cocinetas Basin provides an extensive and well-exposed sedimentary and paleontological record of the past 30 million years.

There are very few geologic studies of the Cocinetas Basin. The stratigraphy was first described by Renz (1960), who proposed the formal names, stratotypes, depositional environments, and ages for the various units of the basin (Figs. 1 and 2). Rollins (1965) carried out further detailed descriptions redefining a number of stratigraphic units (Fig. 2). Biostratigraphic data based on micropaleontology (Becker and Dusenbury 1958; Burgl 1960; Lockwood 1965; Renz 1960; Rollins 1965; Zapata 2010) and macropaleontology (Olsson and Richards 1961; Rollins 1965; Thomas 1972) have been previously reported. However, most of these studies are taxonomically outdated, lack of systematic analysis, and are based on

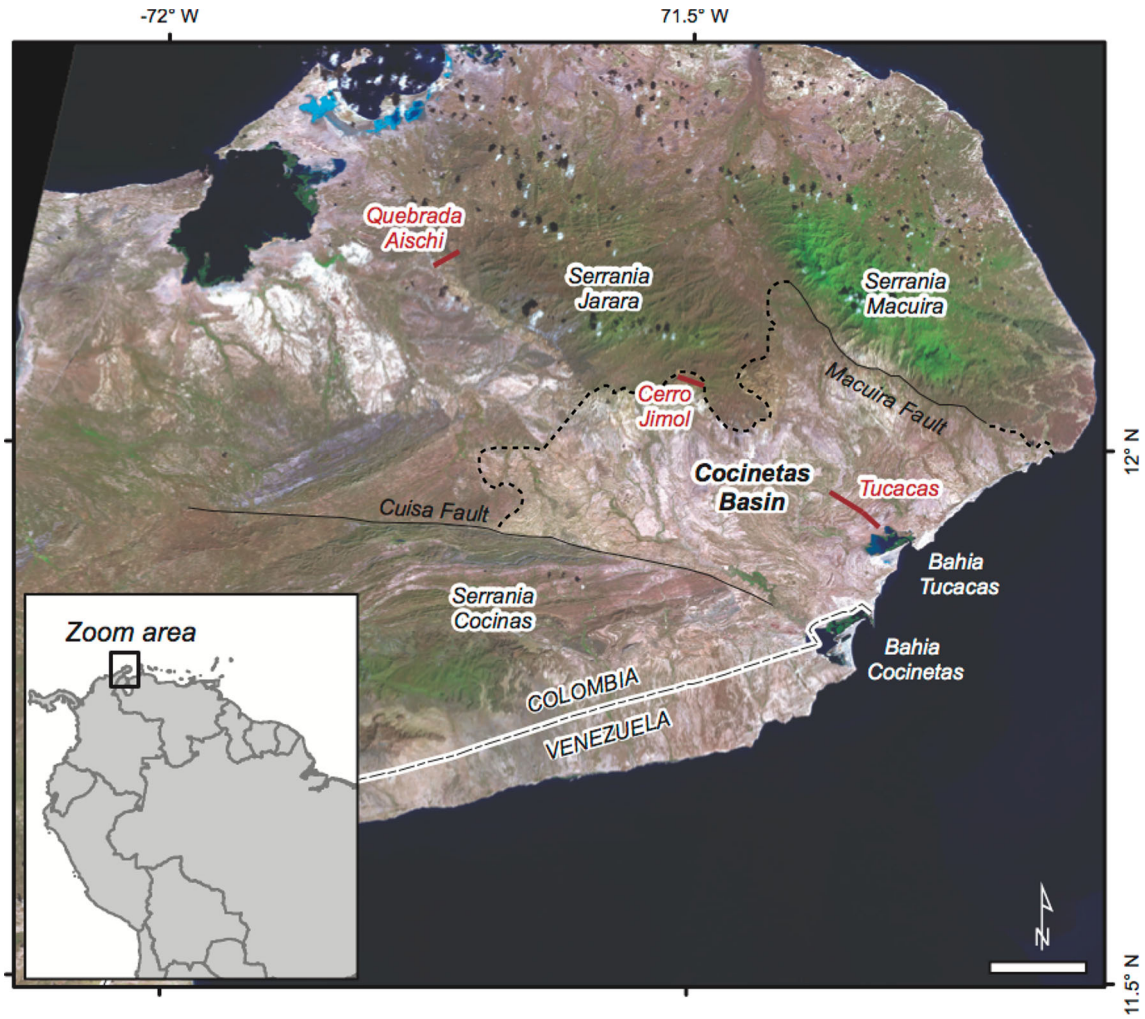


Fig. 1 Regional location of Cocinetas Basin flanked by the Serranías of Cocinas, Jarara and Macuira, in the northern Guajira Peninsula of Colombia, South America. Stratotypes defined by Renz (1960) are shown in *red*. Image from Landsat 8 OLI-TIRS sensor acquired on January 10, 2014 (RGB 543). *Scale bar* is 10 km

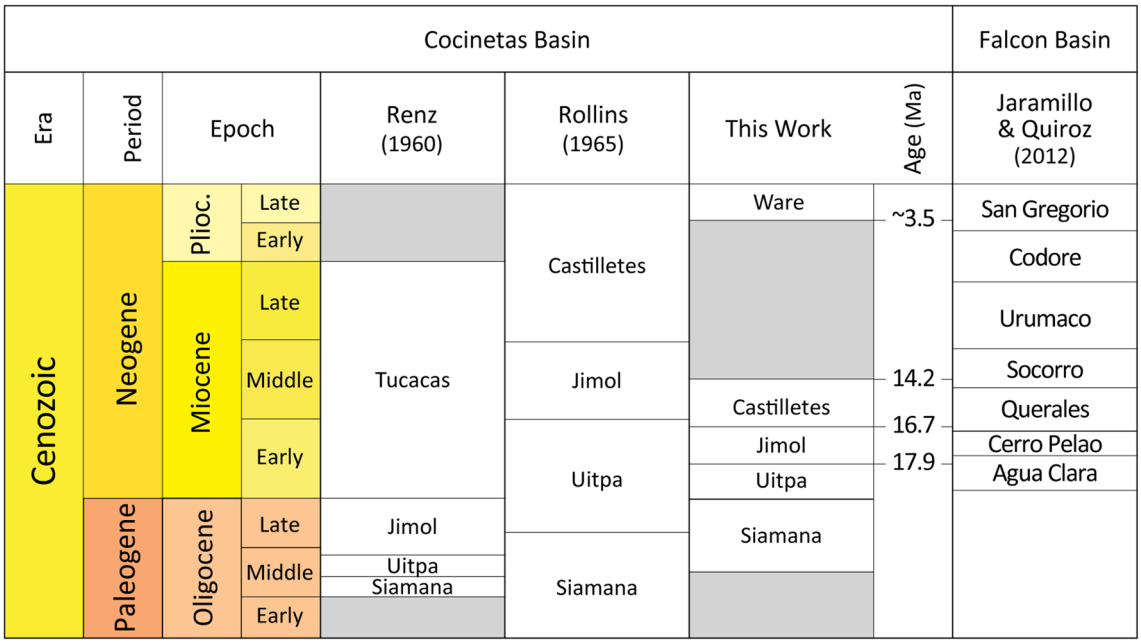


Fig. 2 Historical stratigraphic nomenclature for the Cocinetas Basin, La Guajira, Colombia. *Gray color* indicates intervals where sediment was not preserved

paleontological collections of variable quality. A review of macropalaeontological evidence for the age of the Neogene units of the Cocinetas Basin is provided by Hendy et al. (2015) in this issue.

Over the past 4 years, we have conducted extensive fieldwork in the Cocinetas Basin, including geological mapping, lithofacies descriptions, and extensive and systematic collection of microfossils, marine and terrestrial invertebrates, marine and terrestrial vertebrates, and plants. Here, we provide a revised stratigraphy for the Neogene of the Cocinetas Basin, including a redefinition of the Jimol and Castilletes formations, and the description of a new lithostratigraphic unit, namely the Ware Formation (Pliocene). In addition we present a chronostratigraphic framework that is supported by $^{87}Sr/^{86}Sr$ isotopic analyses and marine invertebrate biostratigraphy, and a paleoenvironmental interpretation of the sedimentary succession.

Geological setting

Since the Late Eocene, the northern margin of the South American plate has been affected by right-lateral transpressive tectonism caused by its oblique convergence with the southern margin of the Caribbean plate (Macellari 1995; Pindell and Barret 1990; Zapata et al. 2014). This interaction has caused the fragmentation and eastward migration of several South American blocks including the Paraguaná, Falcon, Maracaibo, Guajira, Perijá, and Santa Marta, and the subsequent opening of pull-apart sedimentary basins along the northern margin of South America, e.g., Cocinetas, Chichibacoa, Falcon, La Vela, and Paraguaná (Macellari 1995; Muessig 1984; Zapata et al. 2014).

The Cocinetas Basin located in the Guajira Peninsula is bounded by the Cocinas, Jarara, and Macuira ranges (Fig. 1). Sedimentation in the basin started during the middle-late Eocene (Macarao Formation) and continued again during the Late Oligocene (Siamana Formation), with a sequence of conglomerates and thick carbonates (Fig. 2) (Macellari 1995; Renz 1960). Overlying the Siamana Formation is the Early Miocene Uitpa Formation, a thick sequence of calcareous mudstone interbedded with lithic sandstones (Renz 1960; Rollins 1965). Overlying the Uitpa Formation are the Miocene Jimol and Castilletes formations (Fig. 2), composed mostly of lithic sandstones and mudstones, which can be highly fossiliferous. The last phase of preserved sedimentation is represented by the Pliocene Ware Formation, a new formation formally proposed herein.

Former lithostratigraphic definition of Neogene units

Renz (1960) formally described the Siamana, Uitpa, Jimol, and Tucacas formations (Fig. 2). Rollins (1965) formally named the Macarao Formation; redefined the Siamana, Uitpa, and Jimol formations; proposed the name Castilletes as a replacement for the Tucacas Formation; and redefined ages and areal distribution for these units (Fig. 2). It should

be noted that Renz (1960) named the Jimol Formation after Cerro Jimol located to the southeast of the Jarara Range and proposed its stratotype in Quebrada Aischi (Fig. 1), outside the boundaries of the Cocinetas basin. Rollins (1965) had a different opinion, and assigned both the Quebrada Aischi and Cerro Jimol sections as belonging to the Siamana Formation. He redefined the areal distribution in some problematic areas as Cerro Jimol and Quebrada Aischi, but accepted the general distribution proposed by Renz (1960). Without defining a new stratotype, he described the Jimol Formation as the sandy limestone, calcareous sandstone, and clay overlying the softer sediments of the Uitpa Formation and underlying the *Ostrea*-bearing limestone at the base of the Castilletes Formation. Rollins (1965) reported a thickness of 614 m for the Jimol Formation and assigned a Middle Miocene age based on the molluskan assemblage of *Clementia dariena*, *Cardium gatunese*, *Arca chiriquiensis bolivari*, *Arca grandis colombiensis*, and *Turritella* aff. *supraconcava*. While these 'species' are largely supportive of a Late Miocene age (following current biostratigraphic knowledge), the identifications and interpretation of Rollins (1965) need to be revised. A review of macropalaeontological evidence for the age of the Neogene units of the Cocinetas Basin is provided by Hendy et al. (2015) in this issue. The foraminiferal biotas that occur in the lower and upper parts of the Jimol Formation are associated with the *Miogypsina günteri* and the *Miogypsina intermedia* biozones (Renz 1960). These assemblages were initially reported as indicating a middle to Late Oligocene age (Renz 1960). However, identification of *Globorotalia semivera* (Hornibrook) (=*Paragloborotalia semivera*) by H. Duque Caro from the Jimol Formation (Zapata 2010) supports a Late Early Miocene age (Chaisson and D'Hondt 2000).

The Jimol Formation is overlying conformably by the Castilletes Formation, which is composed mostly of wackestone and packstone biosparite, and fossiliferous sandstone and mudstone. Renz (1960) first named this unit the Tucacas Formation after Bahía Tucacas. However, Rollins (1965) argued that the name Tucacas was likely to create confusion because of the presence of a town of the same name, located in northern Venezuela. Rollins (1965), therefore, re-erected the presently used name, Castilletes Formation, after the village of Castilletes, located in La Guajira Peninsula. Rollins, however, retained the type section proposed by Renz for the Tucacas Formation, which is located in the area of Bahía Tucacas (Fig. 1). Renz (1960) reported a thickness of 800 to 900 m at the type section, whereas Rollins (1965) measured the section again and estimated a thickness of 692 m, listing *Ostrea pulchana*, *Chlamys (Aequipecten) plurinomis morantensis*, and *Pecten bowdenensis* among other taxa collected at the stratotype. Renz (1960) dated the base of the Formation as earliest Miocene based on the larger foraminifer *Miogypsina antillea*. Rollins (1965), however, accepted that none of the macrofauna collected were diagnostic for age, although they seem to suggest a Pliocene age (following current biostratigraphic knowledge). As noted above, Rollins's (1965) identifications and interpretation are in doubt and are critically assessed by Hendy et al. (2015) in this issue. Rollins (1965 p. 59) agreed with Renz (1960) that the base of the Castilletes was in the Miocene, but argued that the top of the unit was Pliocene on the basis of its stratigraphic position (Fig. 2). A diverse foraminiferal assemblage from the lower part of the Castilletes Formation has been described (Burgl 1960), including the planktonic foraminifera *Globigerina trilocularis, Globigerinoides rubra, Globigerinoita morugaensis, Globorotalia mayeri,* and *Globorotalia praemenardii*. Of these, *G. mayeri* (=*Paragloborotalia mayeri*) and *G. praemenardii* (=*Menardella praemenardii*) are presently regarded as indicative of the early Late Miocene (Chaisson and D'Hondt 2000; Rincón et al. 2007).

Methods

We carried out extensive geological mapping aided by analysis of high-resolution satellite imagery to improve or determine the location of contacts and areal distribution of the Jimol, Castilletes, and Ware Formations. This process was facilitated by the landscape, in part because the region is very dry and strata are well exposed and easily seen in satellite imagery. The geologic map of Irving (1971) was used as the base map. Initial field mapping identified units by their lithology and topographic expression. We controlled boundaries between units with transects along both the strike and the dip. The field map was refined with satellite imagery from multiple sensors (Table 1). Multiple band ratios from Aster and Landsat imagery were calculated and different combinations were displayed as RGB to aid in the delineation of specific lithologies (Qari et al. 2008; Rawashdeh et al. 2006; Schetselaar et al. 2007; Van der Meer et al. 2012). We used high-resolution imagery (GeoEye-1) during subsequent expeditions to improve the field map. Edge analysis was performed to highlight features such as lineaments (mostly in the NE direction) and areas with vegetation, which are usually within specific geologic units (i.e., coquinas and alluvial plains). Lineaments, faults, geologic unit contacts, and beds from previous maps were then updated through a visual assessment of imagery products. The final geologic map also includes field localities and the geographic start and end points of the new stratigraphic sections. All field data, including fossil collection sites, structural data, and stratigraphic sections, were recorded using global positioning system

Table 1 Relevant characteristics of satellite imagery used for geologic mapping

Sensor	Date (yyyy/mm/dd)	Spatial resolution (m)	Products generated
Landsat ETM+1	3/3/2001	30 (Blue, green, red, NIR, SWIR)[2]	Band ratios
		15 (Panchromatic)	
Aster	4/3/2007	15 (Green, red, NIR)	Band ratios
		30 (SWIR)[2]	
Geoeye−1	7/13/2009	2 (Blue, green, red, NIR)[2]	PCA[3], edge analysis, unsupervised classification
	10/17/2009	0.5 (Panchromatic)	

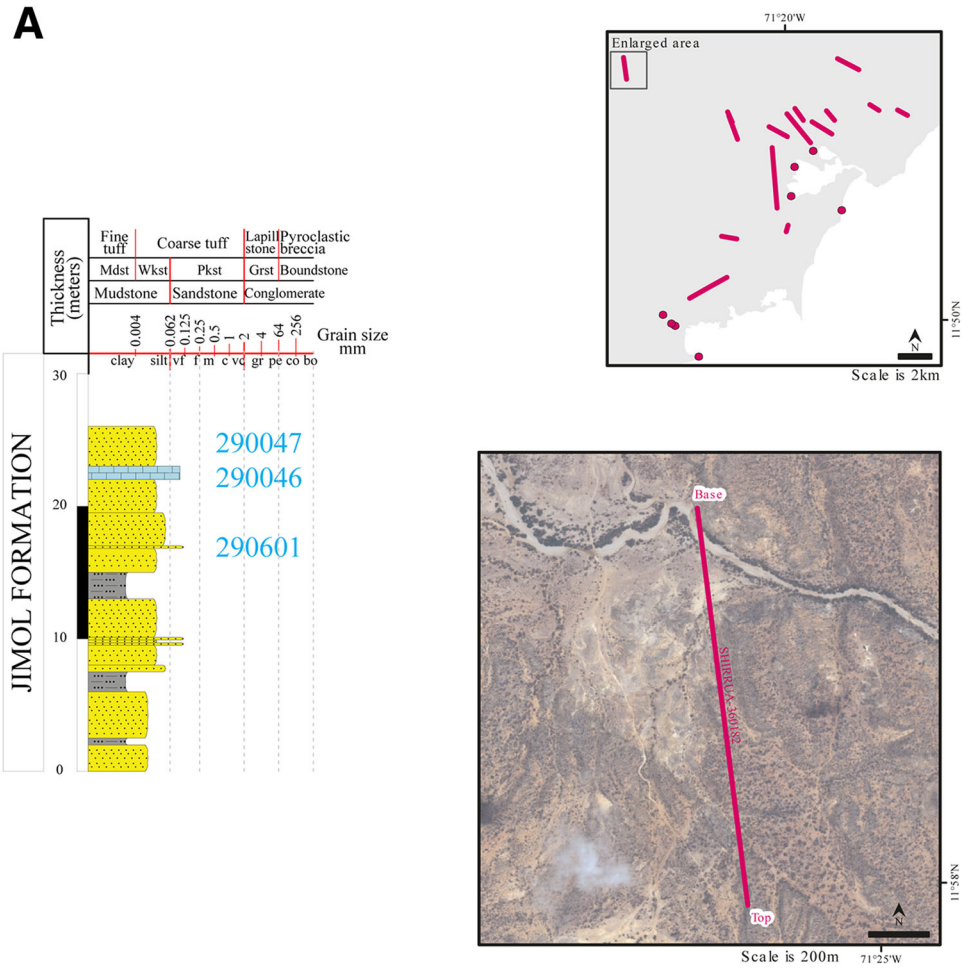
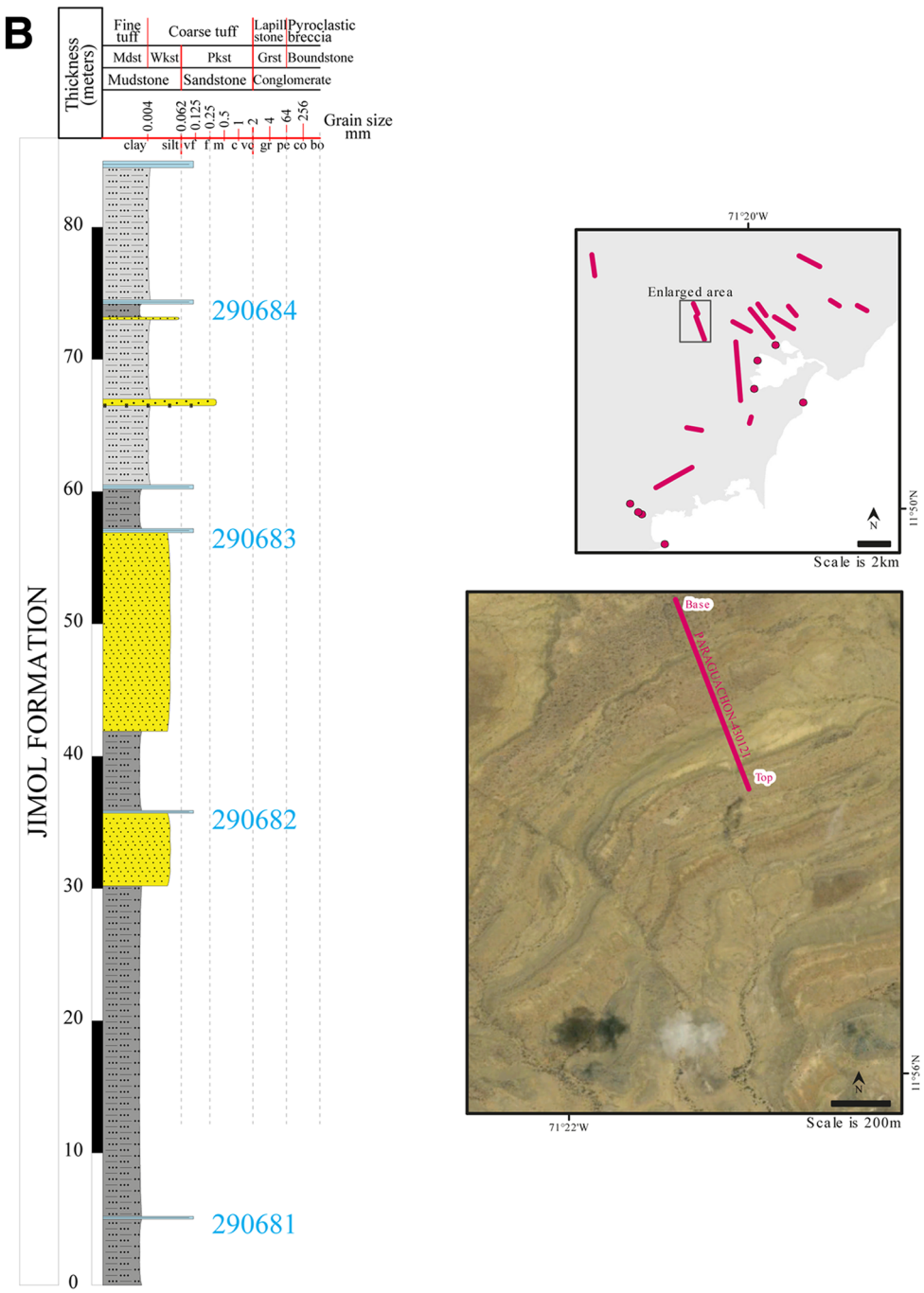


Fig. 3 Stratigraphic sections measured and described in the Cocinetas basin. In each figure the *upper map* shows the location of the stratigraphic sections and the *lower map* shows detailed satellite image of the area where the stratigraphic section was measured. **a** Shirrua, Locality 360182; **b** Paraguachon, Locality 430121; **c** La Tienda, Locality 290432; **d** Kabarauremana, Locality 430214; **e** Kaitamana, Locality 430118; **f** Shorotiju, Locality 430119; **g** Patajau Sur, Locality 430105; **h** Patajau North, Locality 430103; **i** Vertebrates, Locality 170533; **j** Yotojoro, Locality 430203; **k** Aiptiamana, Locality 430169; **l** Long, Locality 150514; **m** Topio Este, Locality 290825 and Topio Oeste, Locality 430170; **n** Shavo, Locality 430200; **o** Puerto López Sureste, Locality 290609; **p** Bahía Tucacas Norte, Locality 430115; Bahía Tucacas Medio, Locality 430116 and Bahía Tucacas Sur, Locality 430117; **q** Punta Gorda Sur-290617; **r** Padsua Este, Locality 430112; Padsua Sur, Locality 430113 and Padsua Norte-430205; **s** Punta Gorda Norte, Locality 430102; **t** Estacion De Policia, Locality 430052; **u** Bahía Cocinetas, Locality 430120

(GPS) units. Image processing was performed with IDRISI Selva (Clark Labs), and vector editing and assemblage of map products were carried out in ArcGIS v 10.0 (ESRI).

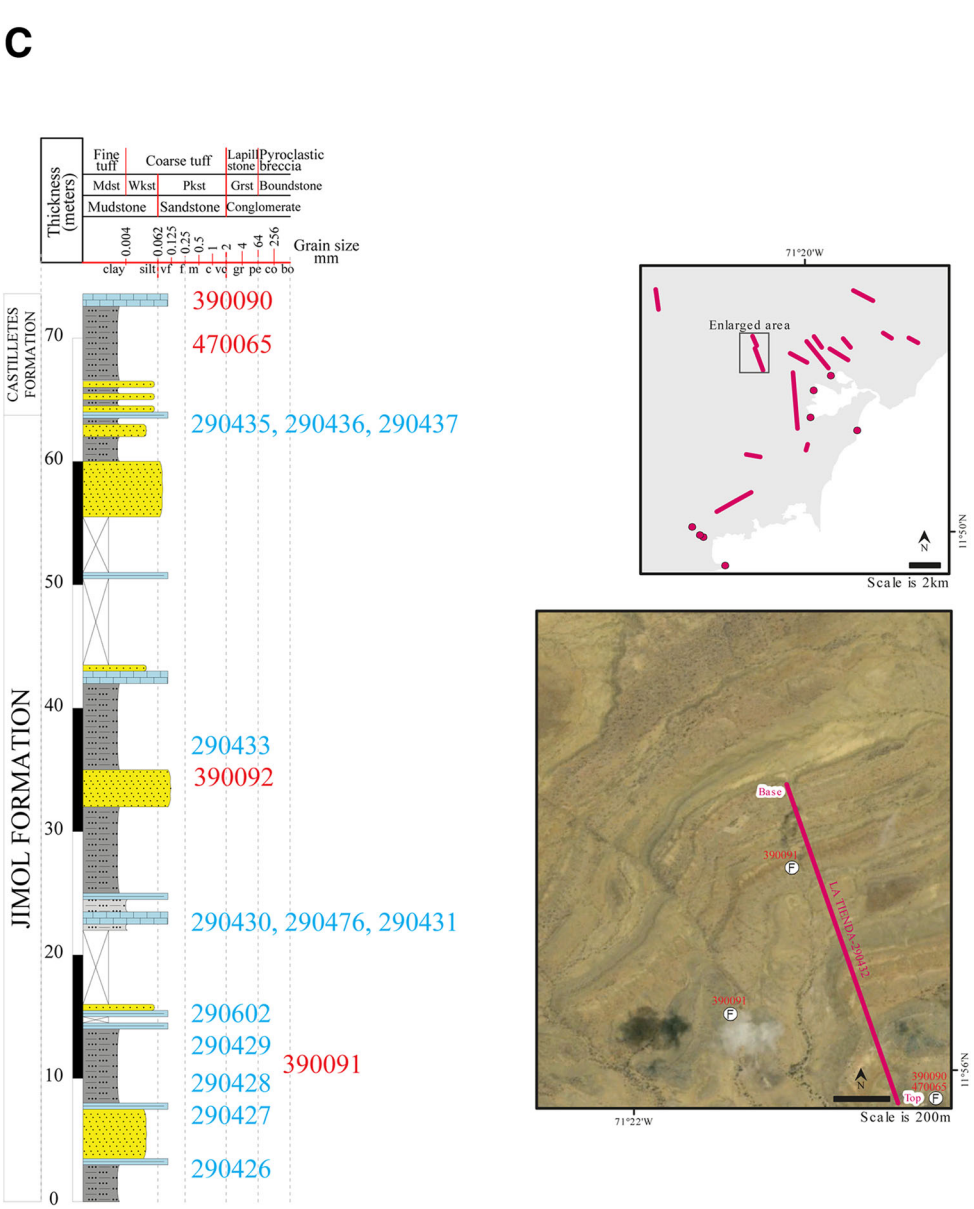
Twenty-six stratigraphic sections were measured (Fig. 3) and correlated using fieldwork observations, macrofaunal composition, and the results of $^{87}Sr/^{86}Sr$



isotopic analyses (Online Resource 1). Lithological descriptions and classifications were done following Dunham (1962) nomenclature for carbonate rocks and Folk (1980) nomenclature for terrigenous rocks. A Jacob's staff was used to measure stratigraphic sections where feasible. GPS and geologic compass data, tied to satellite imagery, were used to measure cover intervals. We used SDAR software (Stratigraphic Data Analysis in R) to digitize stratigraphic data collected in the field. SDAR software is developed in the R language (R Development Core Team 2013) and combined with a MySQL database designed to store stratigraphic data, to graphically represent stratigraphic, sedimentological, and paleontological data (Ortiz et al. 2013).

The development of a chronostratigraphy was achieved through a combination of $^{87}Sr/^{86}Sr$ isotopic analyses and molluskan biostratigraphy. $^{87}Sr/^{86}Sr$ isotopic ratios can be measured in marine calcareous shells and marine calcareous sediment, and values can be compared with global ratios of $^{87}Sr/^{86}Sr$ through geologic time to estimate a

Fig. 3 continued



geologic age (Burke et al. 1982; McArthur 1994; Peterman et al. 1970; Wickman 1948). We sampled the thickest and most pristine calcareous shells in marine strata through the upper Jimol, Castilletes, and Ware Formations although we concentrated sampling in apparent intervals of geochronological interest. Following sampling and analytical protocols used in Kirby et al. (2007, 2008) we first ground off a portion of the surface layer of each shell specimen to reduce possible contamination, avoiding areas showing chalkiness or other signs of diagenetic alteration. Powdered samples of approximately 0.01–0.03 g were drilled from the interior of each shell using a hand-held Dremel tool. The powdered calcite samples were dissolved in 100 µl of 3.5 N HNO_3 and then loaded onto cation exchange columns packed with strontium-selective crown ether resin (Eichrom Technologies, Inc.) to separate Sr from other ions (Pin and Bassin 1992). Sr isotope analyses were performed on a Micromass Sector 54 Thermal Ionization Mass Spectrometer equipped with seven Faraday collectors and one Daly detector in the Department of Geological Sciences at the University of Florida. Sr was loaded onto oxidized tungsten single filaments and run in triple collector dynamic mode. Data were acquired at a beam intensity of about 1.5 V for ^{88}Sr, with corrections for instrumental discrimination made assuming $^{86}Sr/^{88}Sr = 0.1194$. Errors in measured $^{87}Sr/^{86}Sr$ are better than $\pm$ 0.00002 (2σ), based on long-term reproducibility of NBS 987 ($^{87}Sr/^{86}Sr = 0.71024$). Age estimates were determined using the Miocene and Pliocene portions of Look-Up Table Version 4:08/03 (Howarth and McArthur 1997;

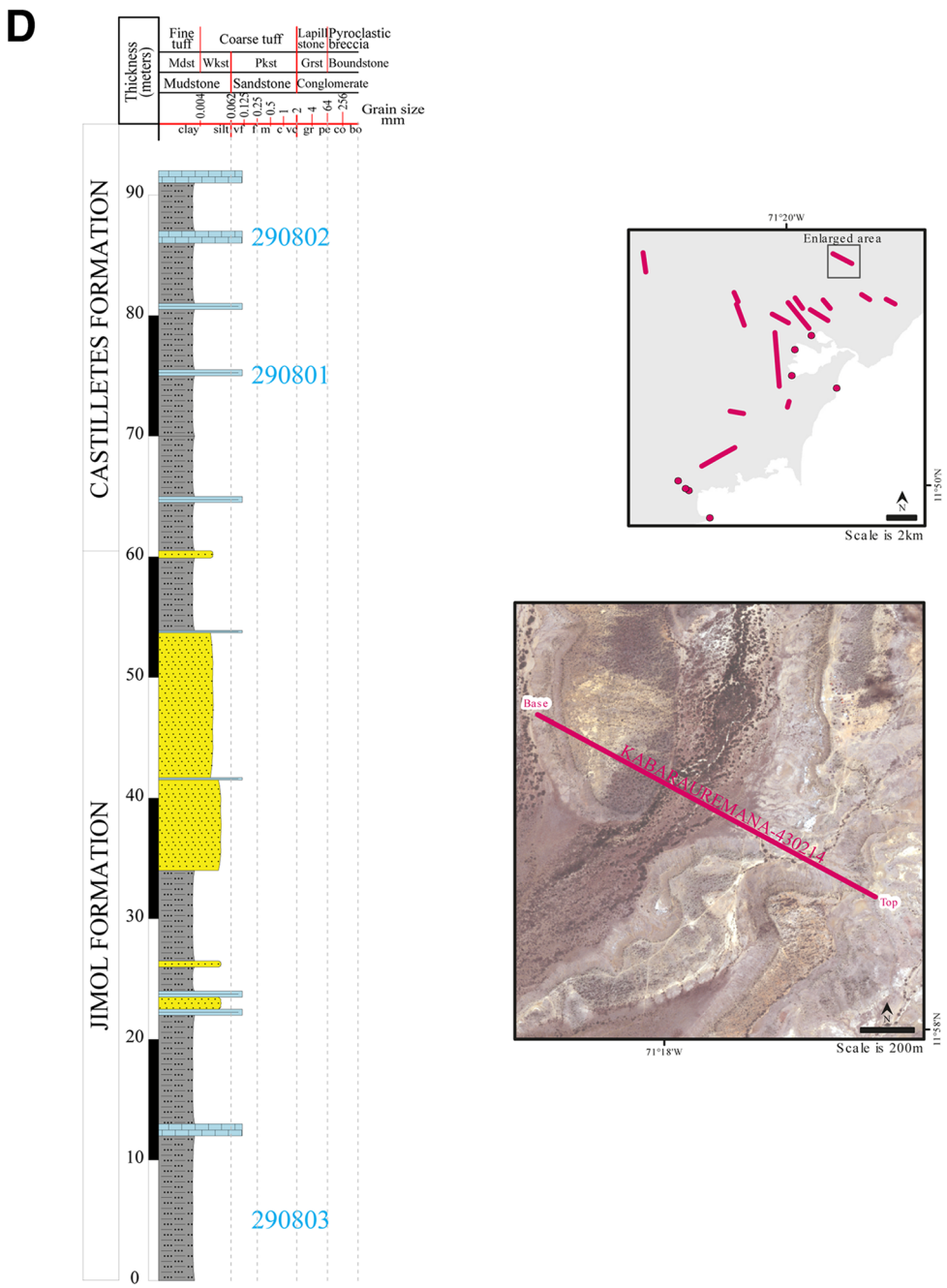


Fig. 3 continued

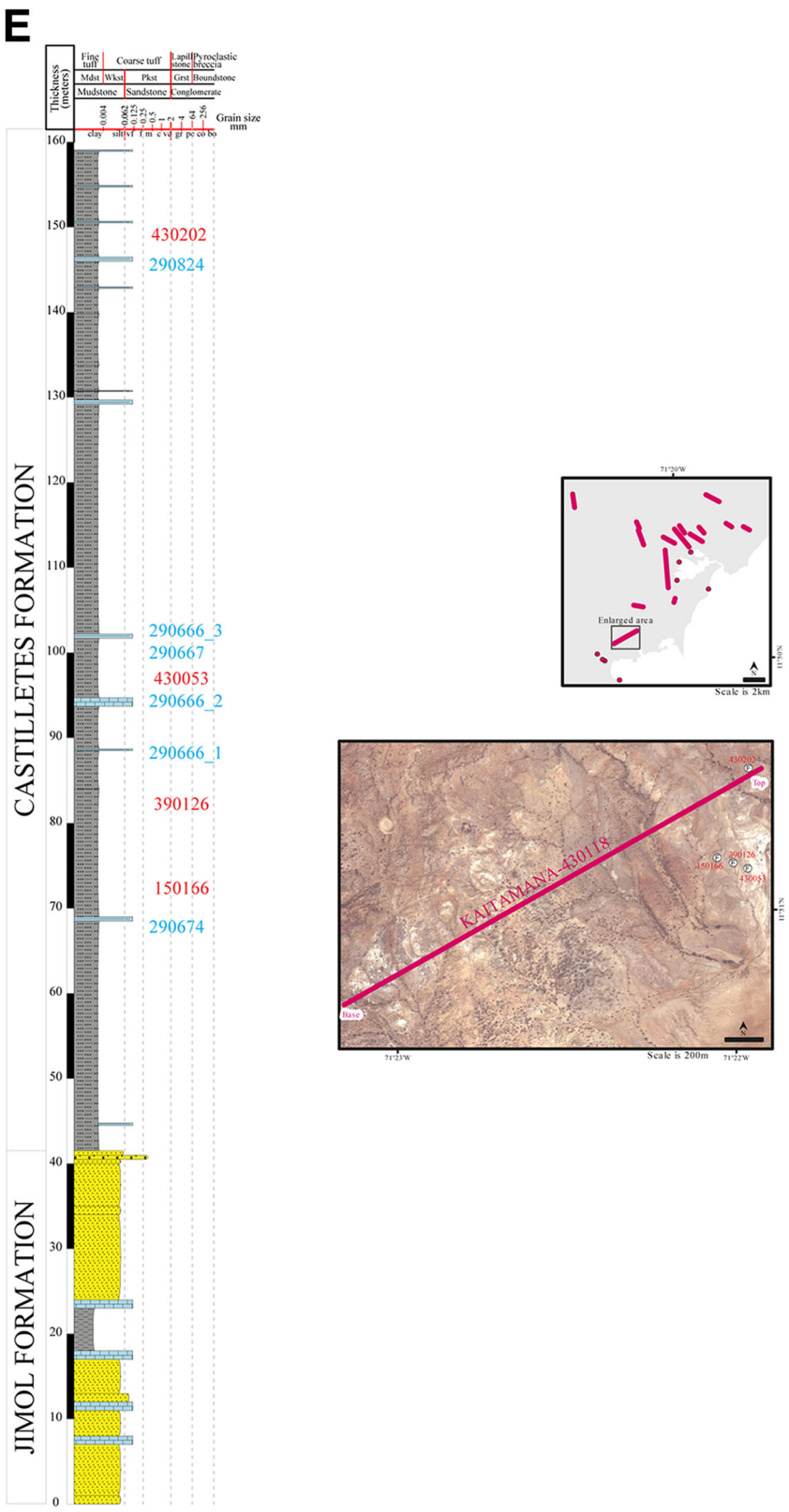
McArthur et al. 2001) associated with the strontium isotopic age.

We used six-digit identification numbers (IDs) to label field localities and stratigraphic sections. IDs correspond to consecutive numbers assigned in the field by the geologist. IDs for stratigraphic sections refer to the base point of each section. Most field localities are related to a single stratigraphic section, which determined their stratigraphic position. A single locality may include one or more samples, or field observations. Each individual specimen or rock collected has also a unique STRI-ID number together with the locality ID. All information on the stratigraphic sections, locality, and sample ID data can be accessed at the STRI PaleoDatabase (http://biogeodb.stri.si.edu/jaramillo2/fossildb/).

Lithostratigraphy

Extensive stratigraphic fieldwork revealed a new boundary between the Jimol and Castilletes formations. In addition, an angular unconformity within the upper part of the

Fig. 3 continued



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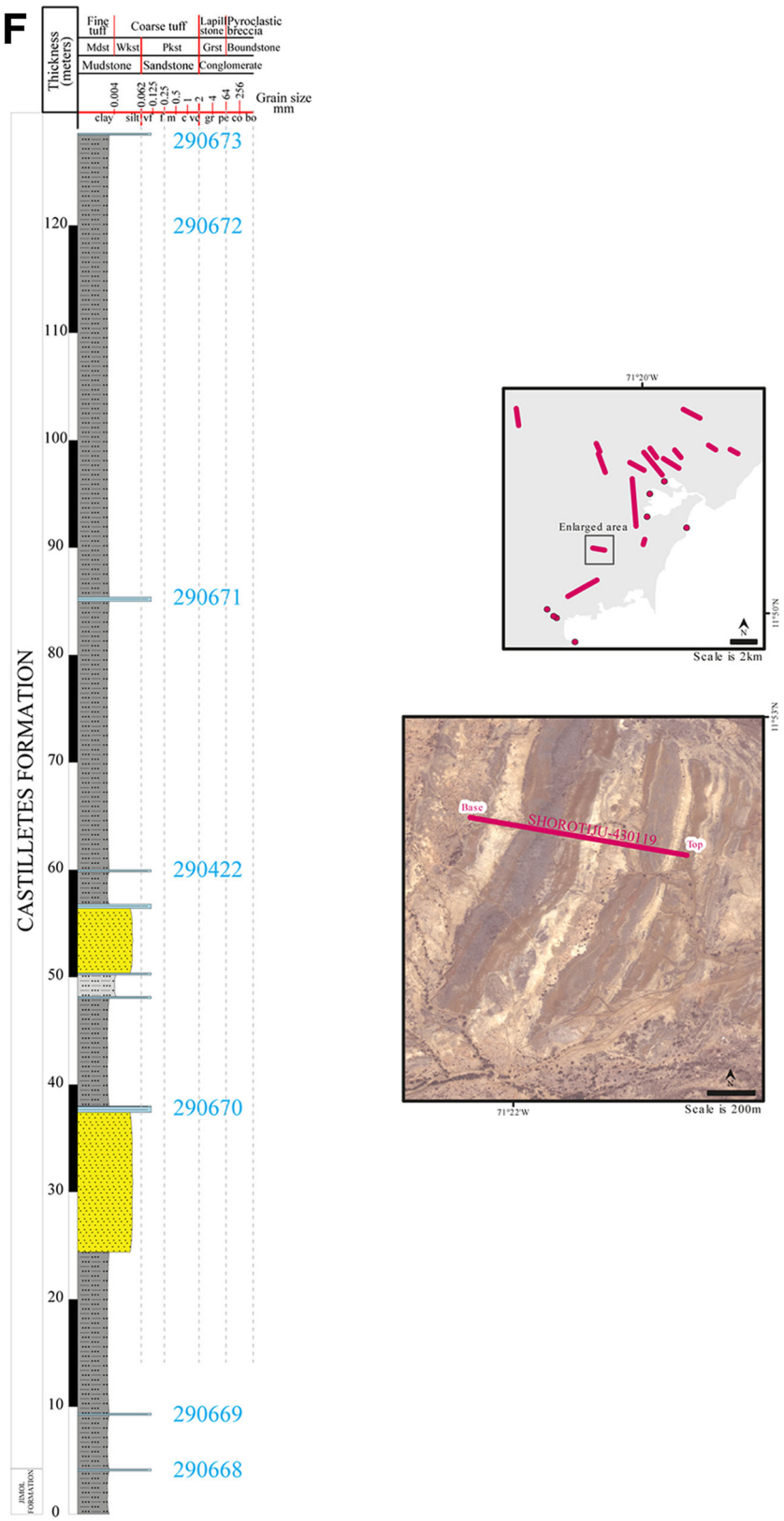

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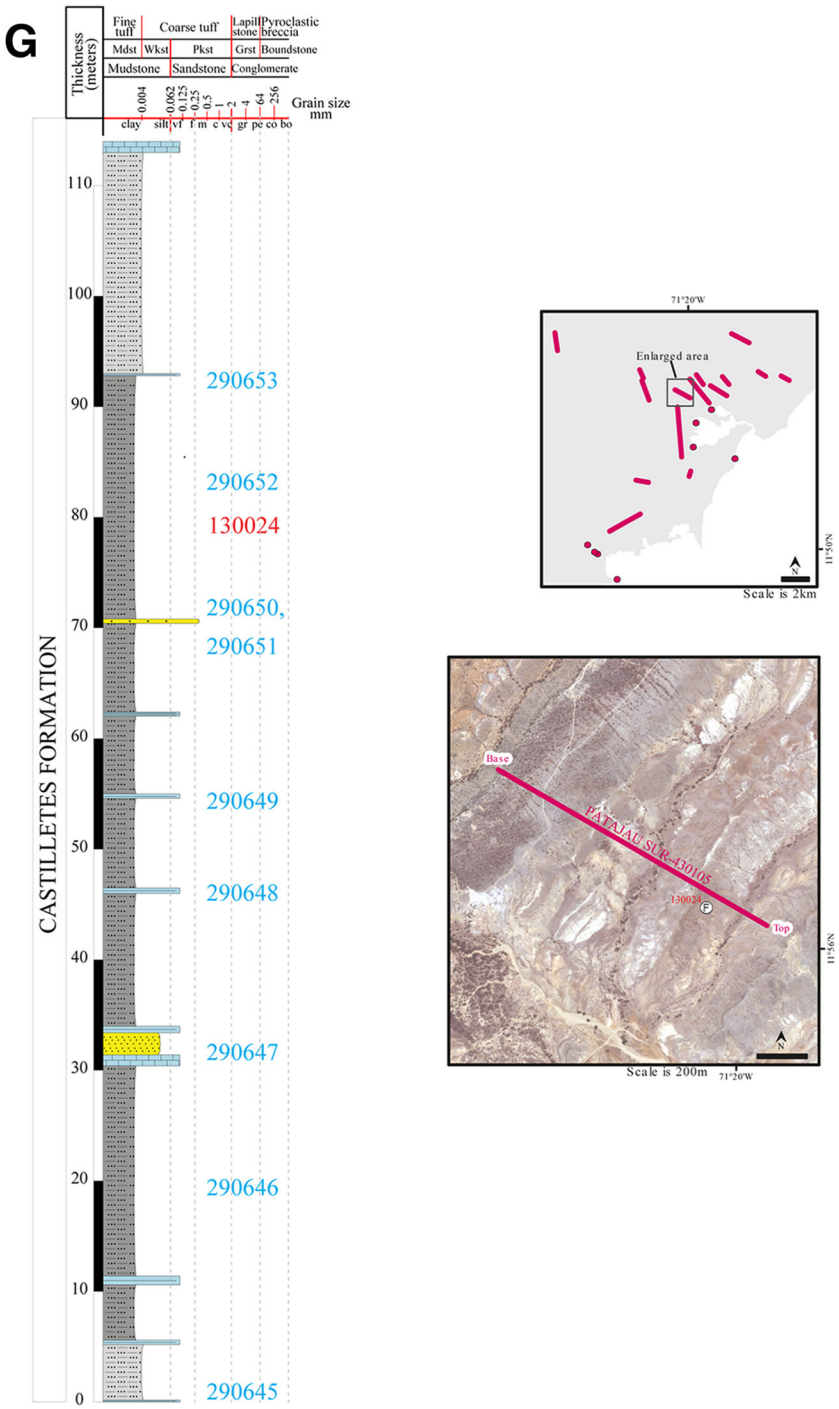
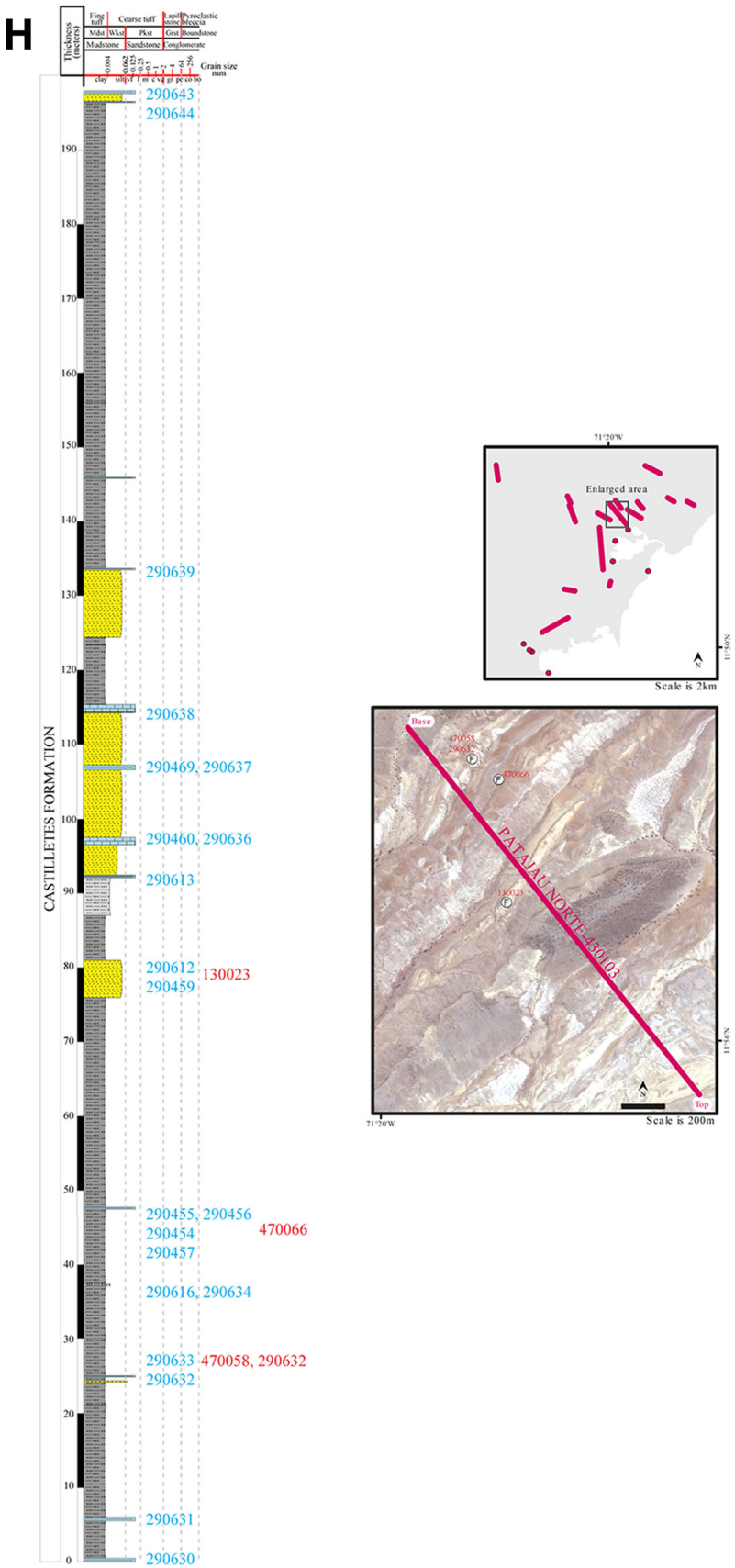


Castilletes Formation of Rollins (1965) was identified in the field. Major changes in faunal composition and the results of $^{87}Sr/^{86}Sr$ dating confirmed these observations and revealed a considerable gap in the geological record from ca. 14.5 Ma to ca. 3.5 Ma (Table 2). These results led us to define a new geological unit, the Ware Formation, which includes those strata above the unconformity, and to exclude the upper part of the Castilletes Formation sensu Rollins (1965) from our new definition of Castilletes. Furthermore, fieldwork revealed a number of impressive and distinctive fossil assemblages in each of the Jimol, Castilletes, and Ware formations.

We described 26 stratigraphic sections comprising the Jimol, Castilletes, and Ware Formations (Figs. 3, 4;

Fig. 3 continued



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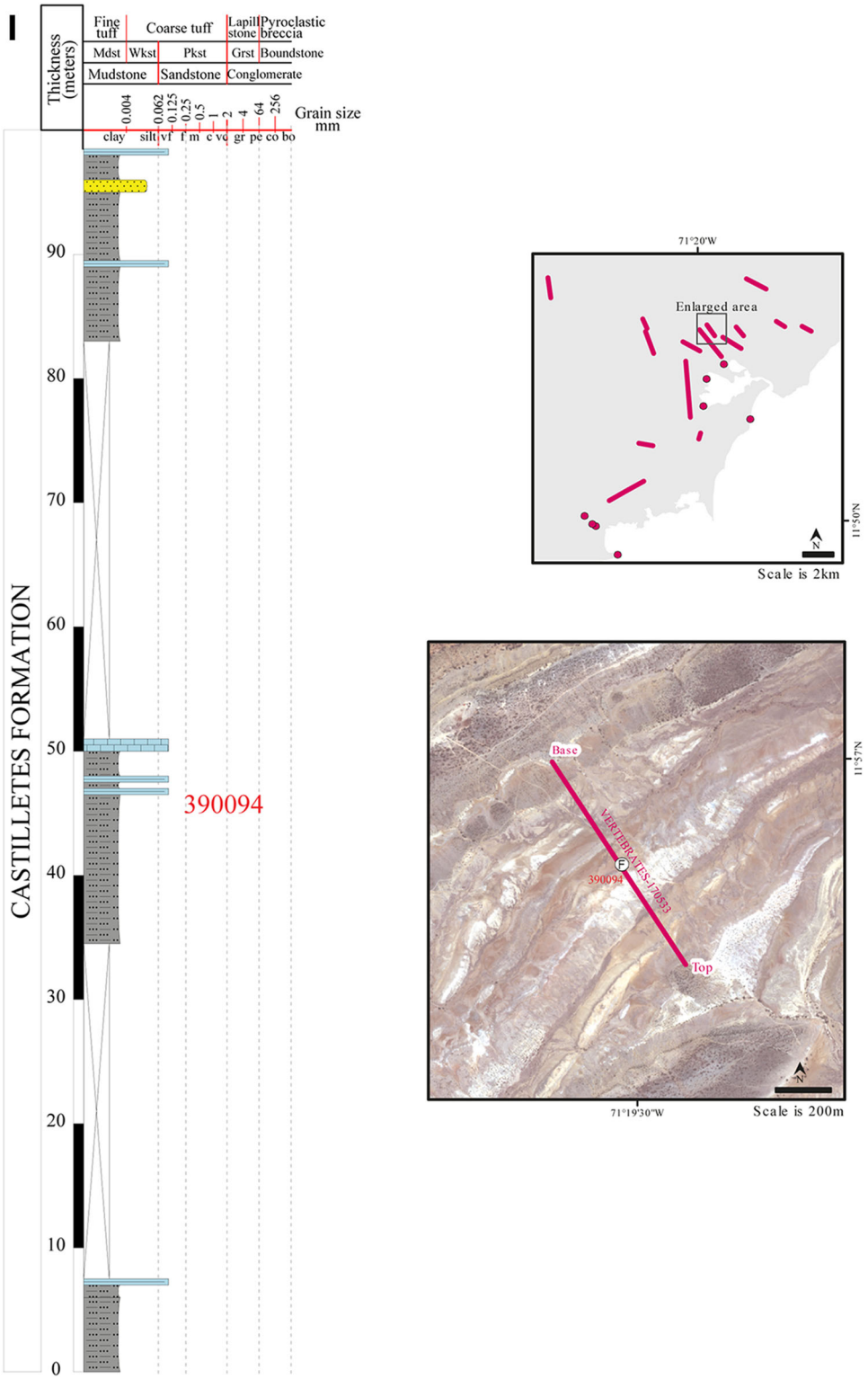

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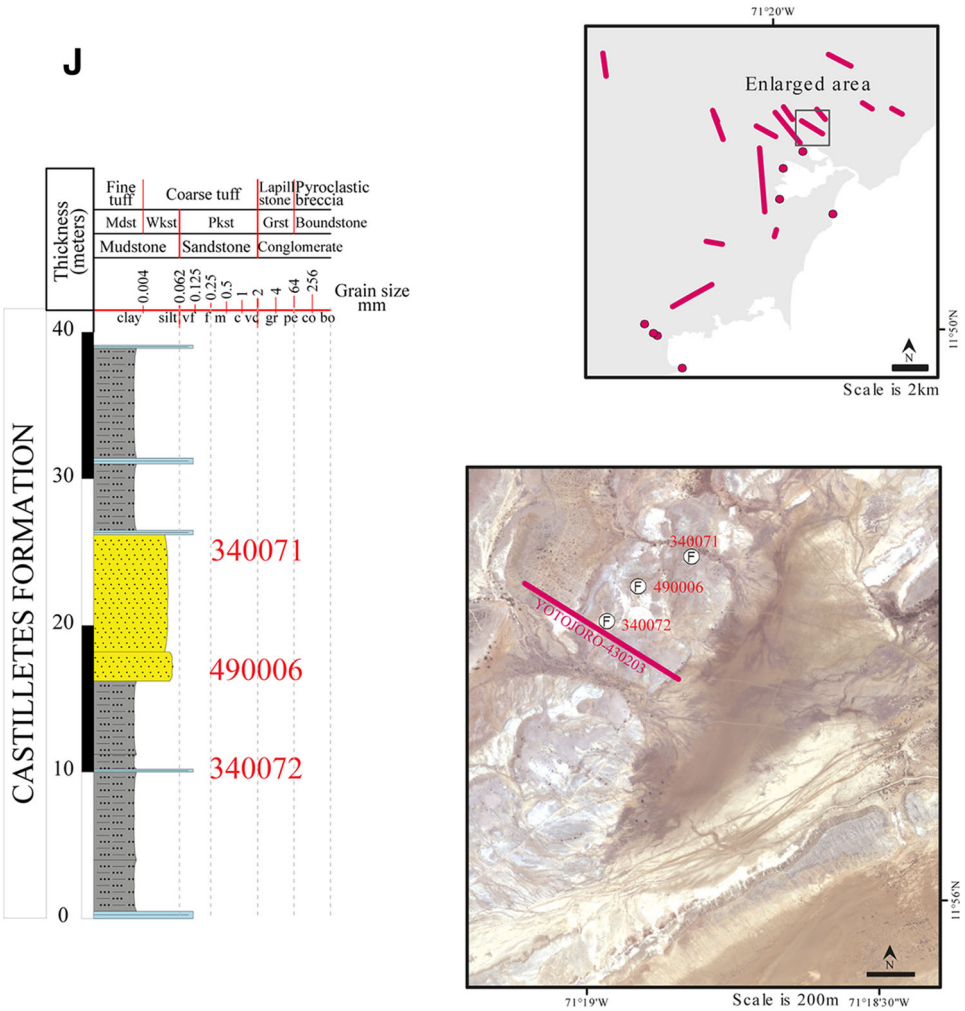


Table 3, Online Resources 1). Four sections define the new composite-lectostratotype of the Jimol Formation (La Tienda—290432, Shirrua—360182, Kaitama—430118, and Paraguachón—430121). Twenty-one sections of the Castilletes Formation were measured. Of those, sections including Patajau Norte—430103, Shavo—430200, Long—170514, Bahía Tucacas Sur—430117, and Topio Este—290825 constitute its new composite lectostratotype. Sections Patsua Sur-Este-430113 and Topio Oeste—430170 contain the angular unconformity separating the Castilletes Formation of the proposed Ware Formation. We measured four stratigraphic sections constituting the Ware Formation, including its type section (Estación de Policia—430052).

Jimol formation

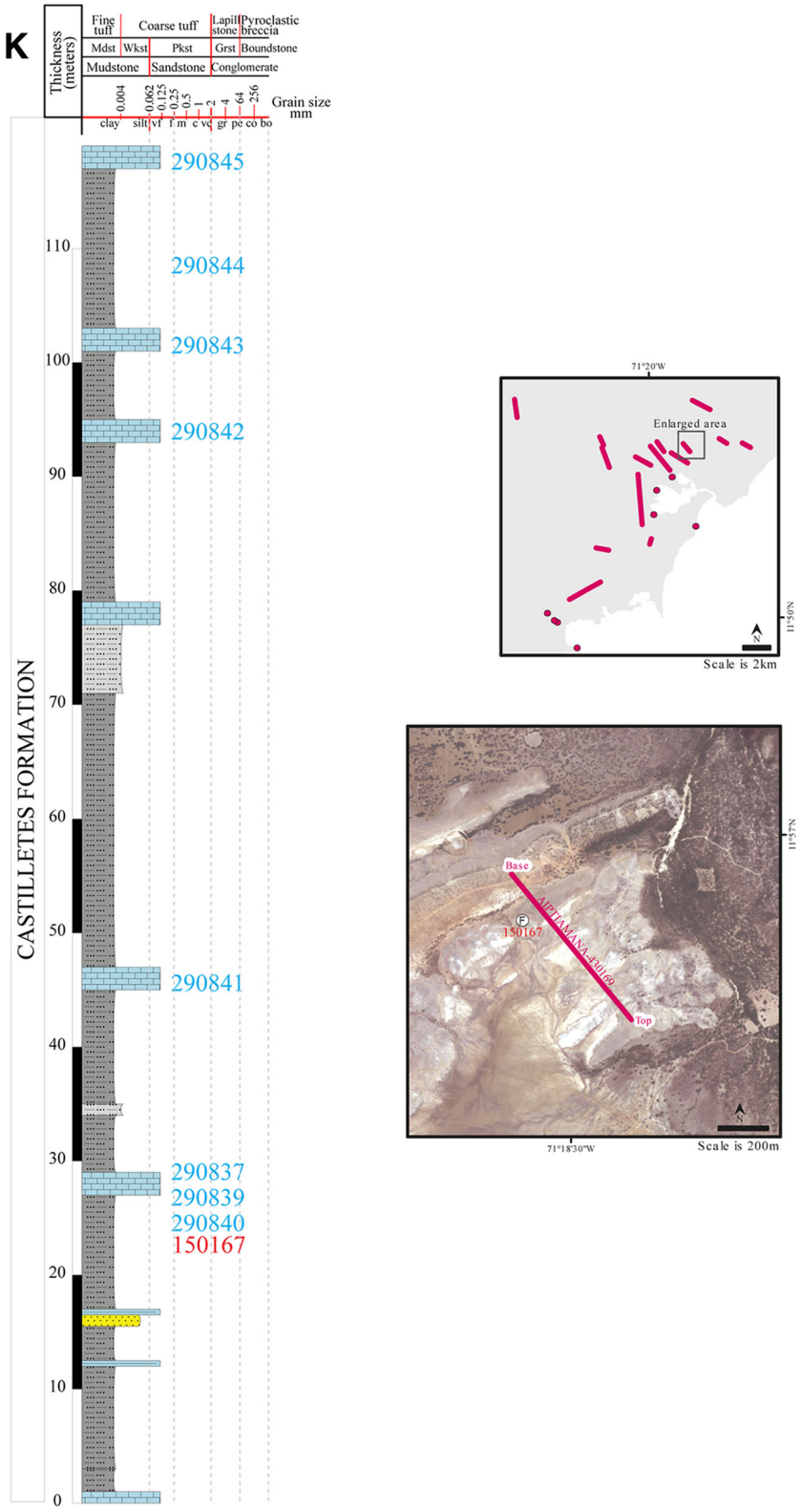
Here, we present a new definition for the Jimol Formation. Depositional environment interpretation will be presented in the following section.

Name Renz (1960) named the formation after Cerro Jimol located in the SE portion of the Jarara Range.

Lectostratotype Paraguachón Valley, between the Arroyo Shirrua and the north boundary of the Patajau Valley. Base of the composite section at 11.97790°N, 71.42234°W, and top at 11.93286°N, 71.35949°W (Figs. 4 and 5).

Description The Jimol Formation is composed of gray calcareous lithic sandstone and lithic sandstone, yellowish gray fossiliferous wackstone to packstone, and gray to brown siltstones and mudstone. At the base, 50 cm to 1 m thick beds of coarse calcareous lithic sandstone and lithic sandstone, with ripples, cross and planar bedding, and fossiliferous wackestone to packstone dominate the sequence. There are occasional ~5 m thick beds of siltstone and mudstone in this part of the sequence. At the top mudstone, fine-grained calcareous lithic sandstone, and lithic sandstone, 5–20 m thick beds dominate the sequence interbedded with 50 cm–2 m thick beds of fine- to medium-grained calcareous sandstone, and fossiliferous wackestone to packstone (Fig. 5).

Fig. 3 continued



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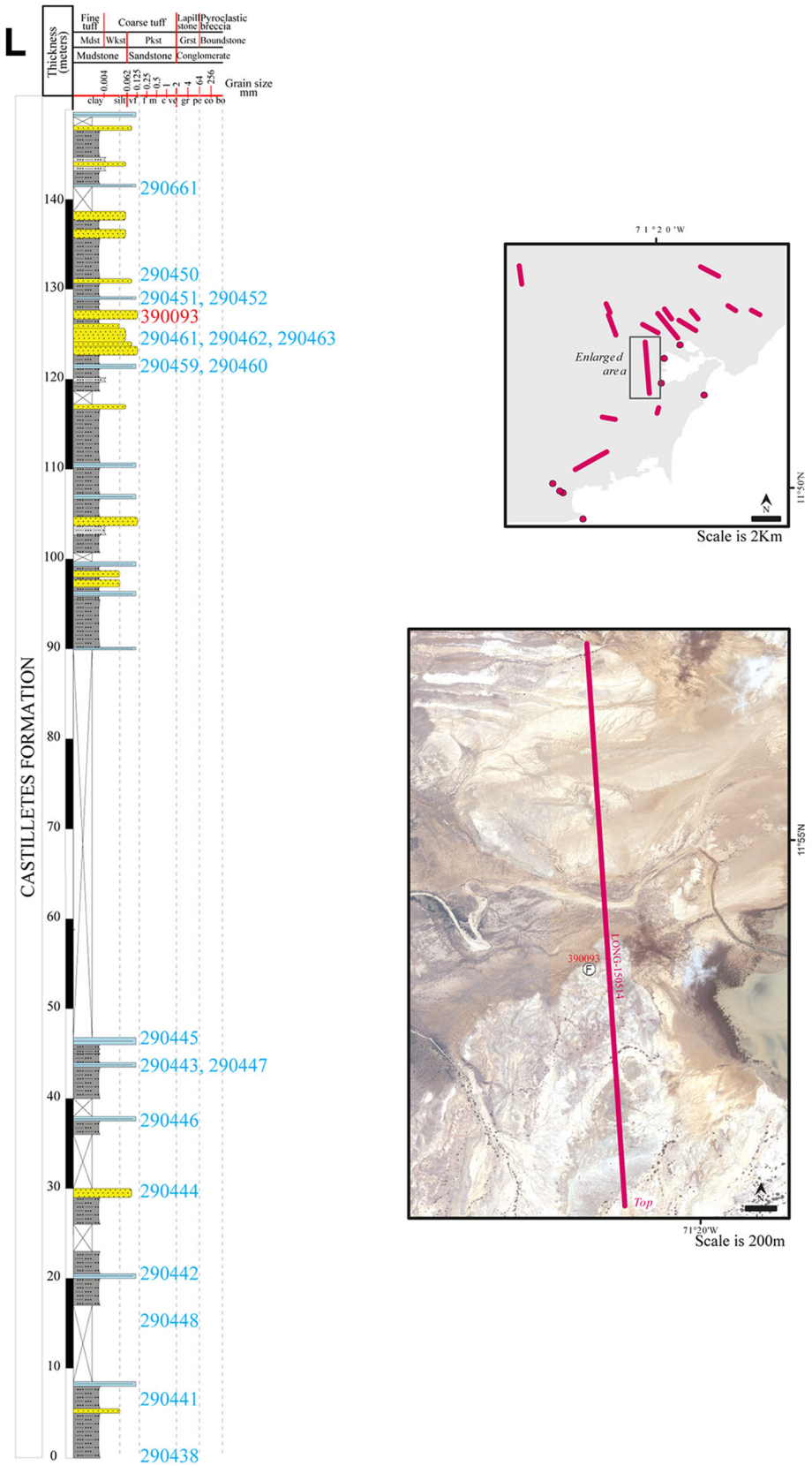

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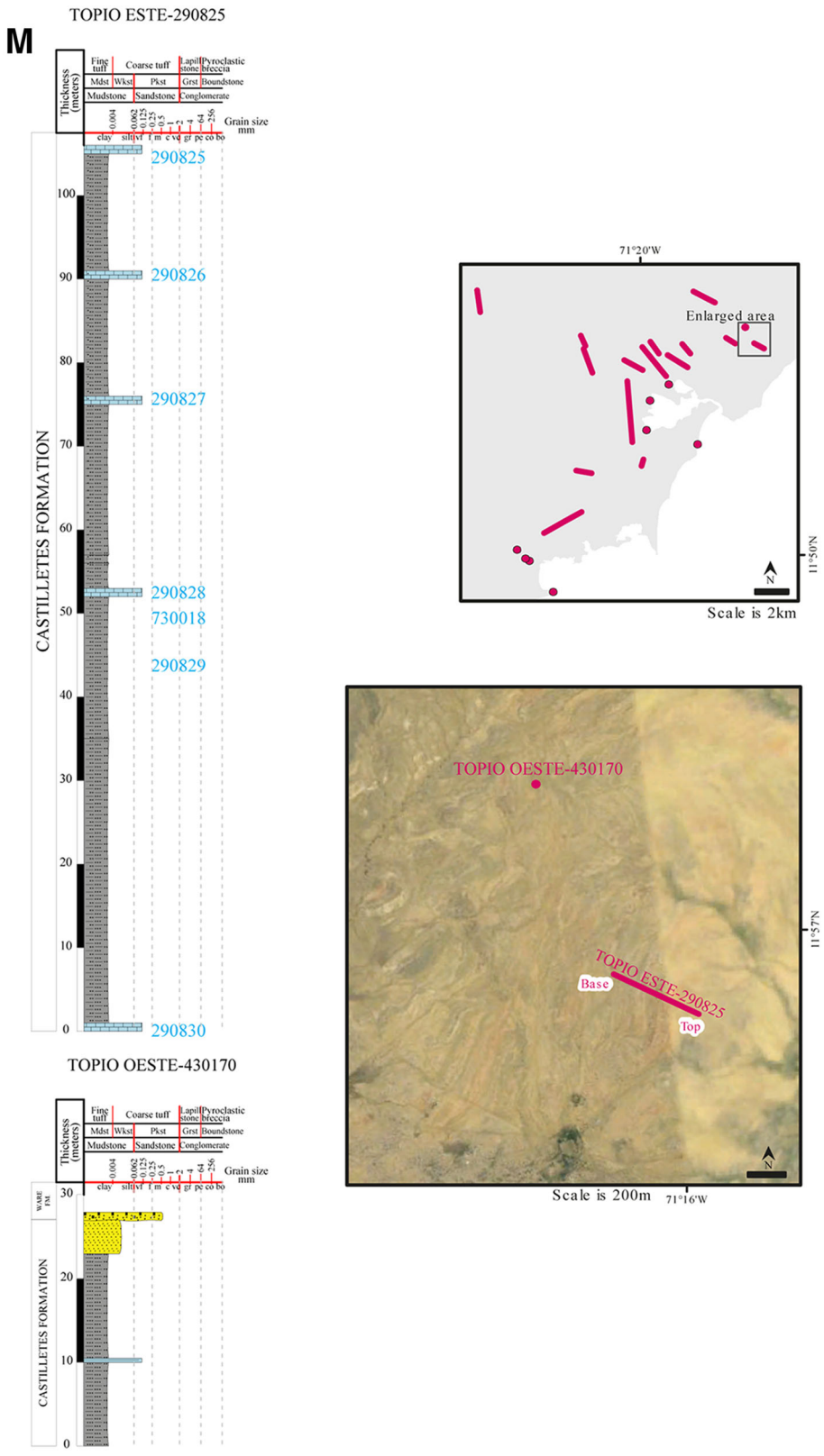
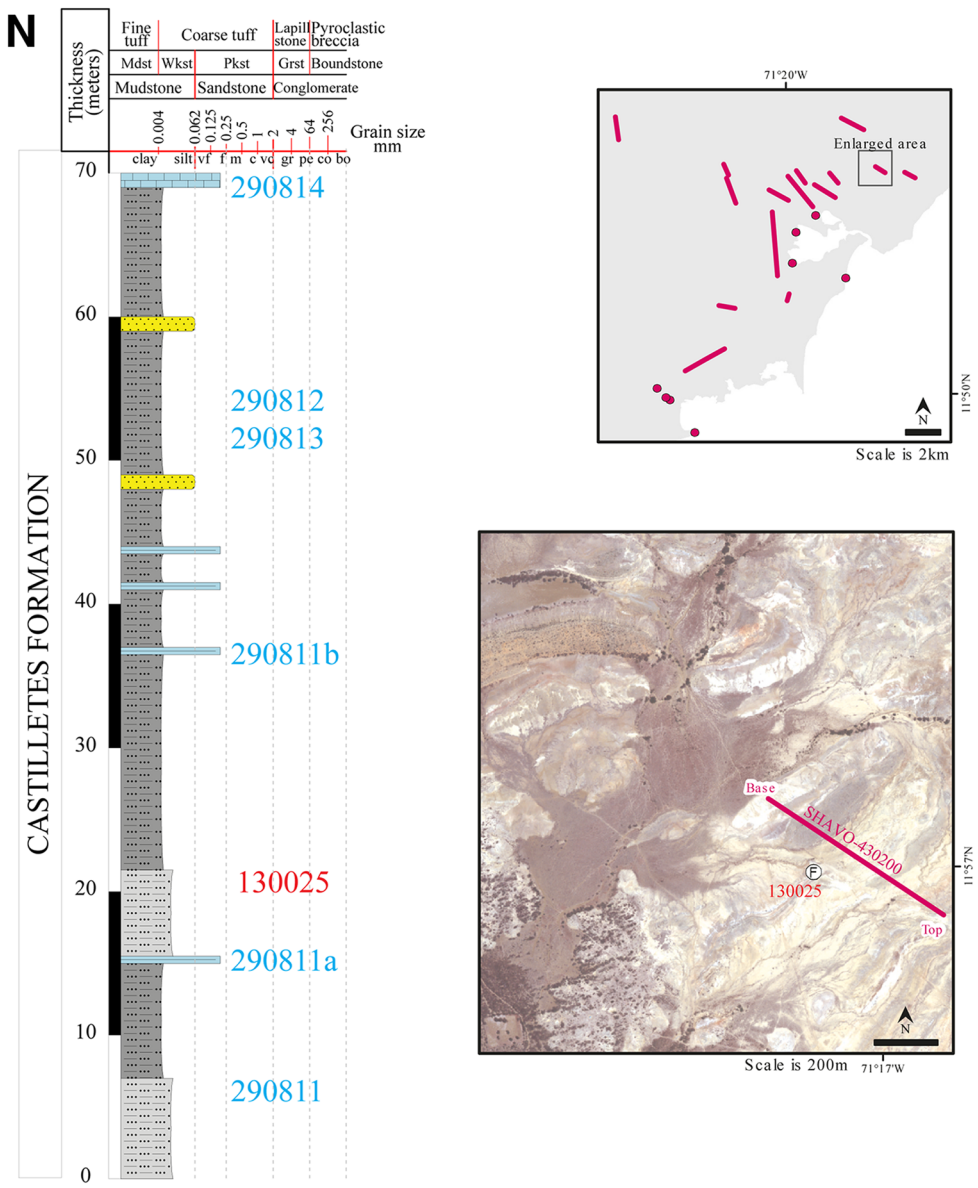


Fig. 3 continued



Lower and upper boundaries The lower boundary of the Jimol Formation was defined by Rollins (1965) as the sandy limestone that makes a prominent scarp over the clays of the Uitpa Formation. We retain this lower boundary in our redefinition of the Jimol Formation, as it is a prominent feature easily seen in the field. We position the new upper boundary at a hardground surface at the top of a fossiliferous wackestone that crops out in the northern limit of Patajau Valley. This surface not only represents a distinct change in facies within the stratigraphic succession from relatively coarse and well-cemented lithologies to those that are fine-grained and unconsolidated of the overlying Castilletes Formation, but also results in a change in topographic expression that can enable the contact to be followed laterally across much of Cocinetas Basin. This facial change is conspicuous and can be noted by the shift from the sandy facies of the Jimol Formation dominated by medium to coarse calcareous lithic sandstone and occasional recessive levels composed of mudstone and siltstone, to the muddy facies of the Castilletes Formation dominated by thick recessive levels of mudstone and siltstone with occasional beds of medium to coarse lithic to

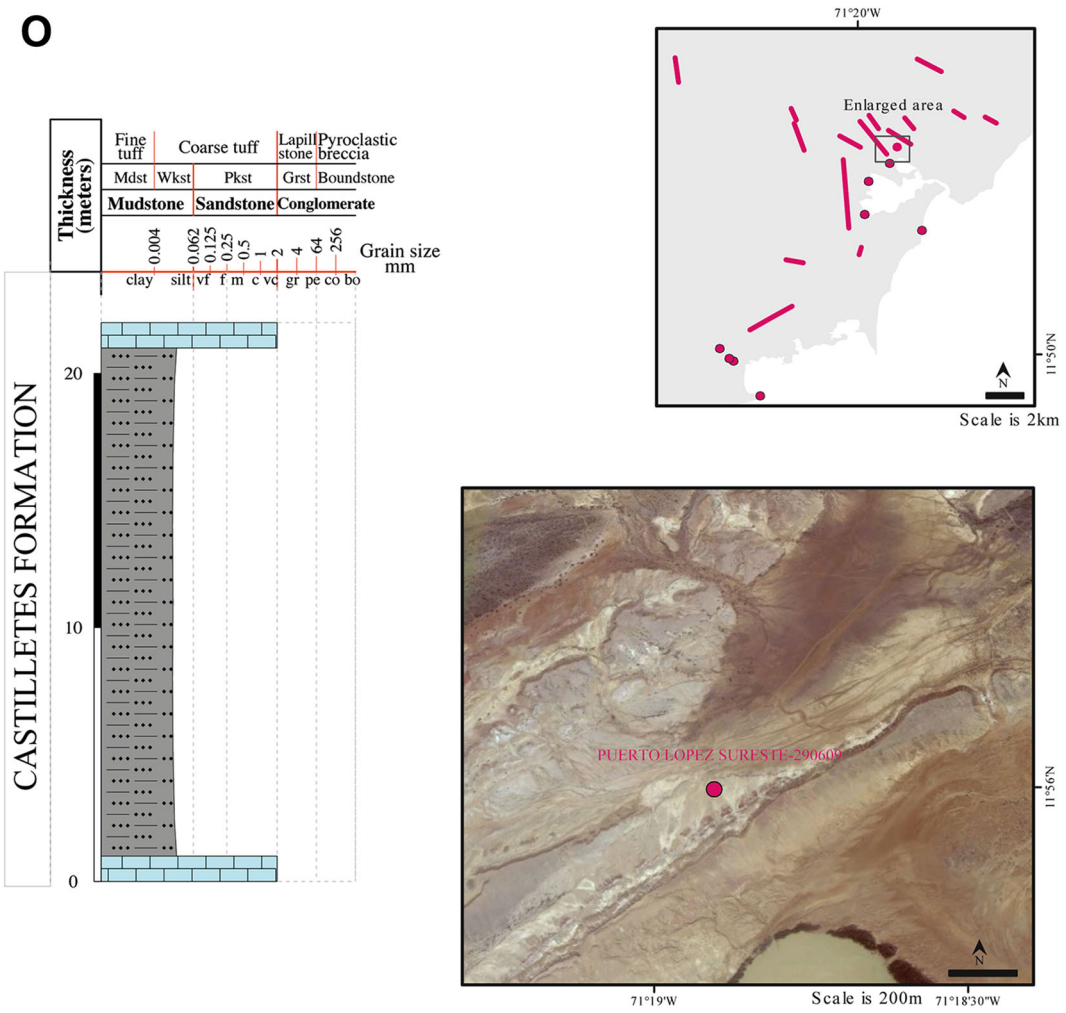


Fig. 3 continued

quartz sandstone, and fossiliferous wackstone to packstone. The hardground surface itself has been observed in multiple transects across this contact. Both boundaries are conformable.

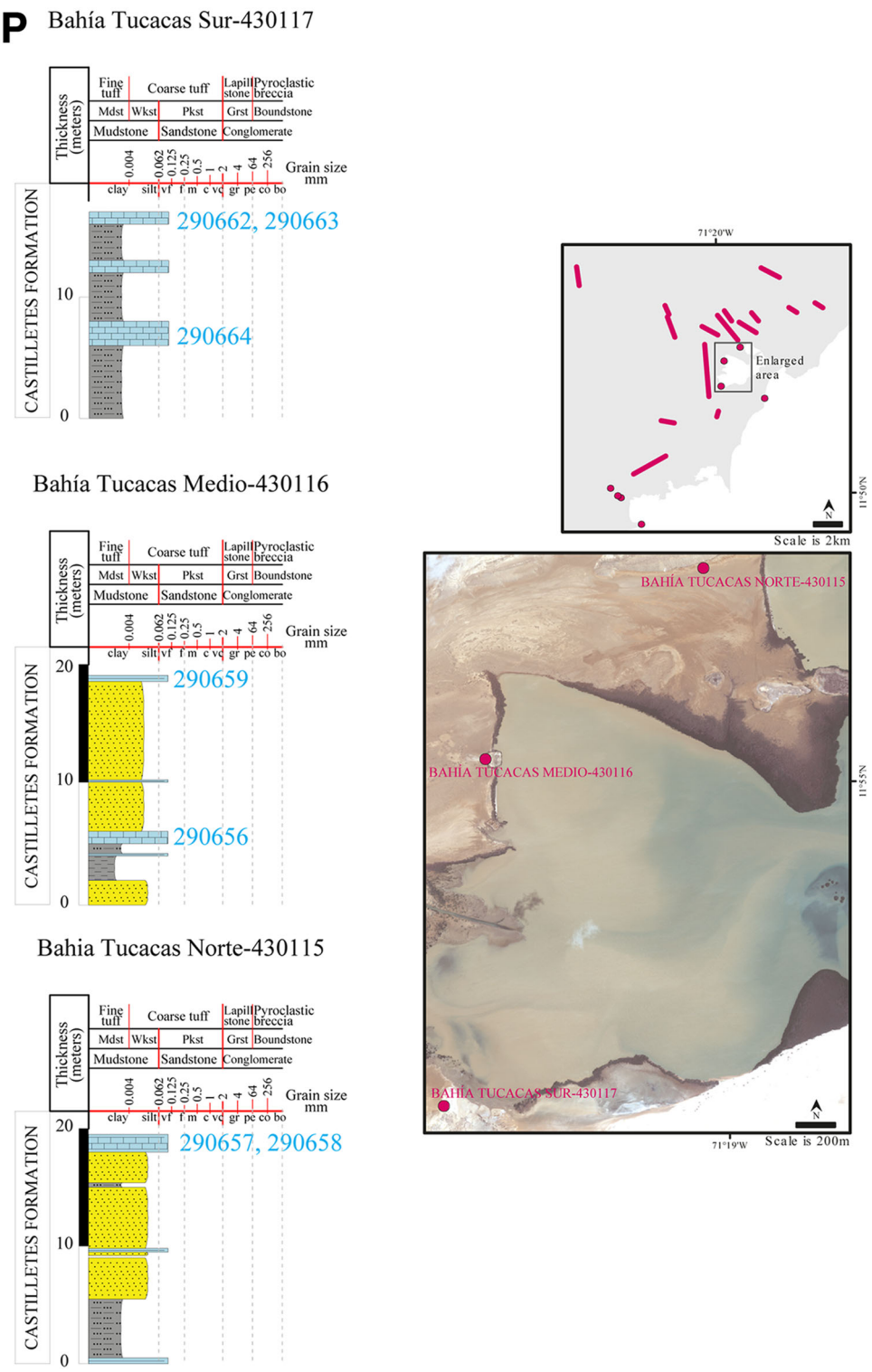
Thickness and regional extent A total thickness of 203 meters was measured in the stratotype, although this should be considered a conservative estimate given the difficulties in measuring poorly exposed strata in the middle portion of the formation. The Jimol Formation forms a NE–SW trended stripe along the central part of Cocinetas Basin, from the Patsua Valley in the south up to Rio Topio in the north (Figs. 5 and 6).

Invertebrate palaeontology Dominant taxa of the Jimol Formation include *Turritella, Anadara (Cunearca)*, *Crassostrea*, *Dallocardia*, and *Pitar*. Other characteristic taxa include *Potamides, Neverita, Glossaulax, Orthaulax, Melongena, Turbinella, Conus, Tucetona, Glyptoactis, Eucrassatella, Clementia,* and *Macrocallista.* Around 103 'species' of mollusks (51 bivalves, 51 gastropods, and 1 scaphopod) have been identified from the formation (see Hendy et al. (2015), in this issue, for a detailed description of this assemblage).

Vertebrate Palaeontology: Two specimens of Crocodilia have been found in two different localities (Tables 4, 5; Online Resource 2). Otoliths of bony fishes and teeth of sharks (Squaliformes, Lamniformes, and Carcharhiniformes) and rays (Myliobatiformes) also have been found.

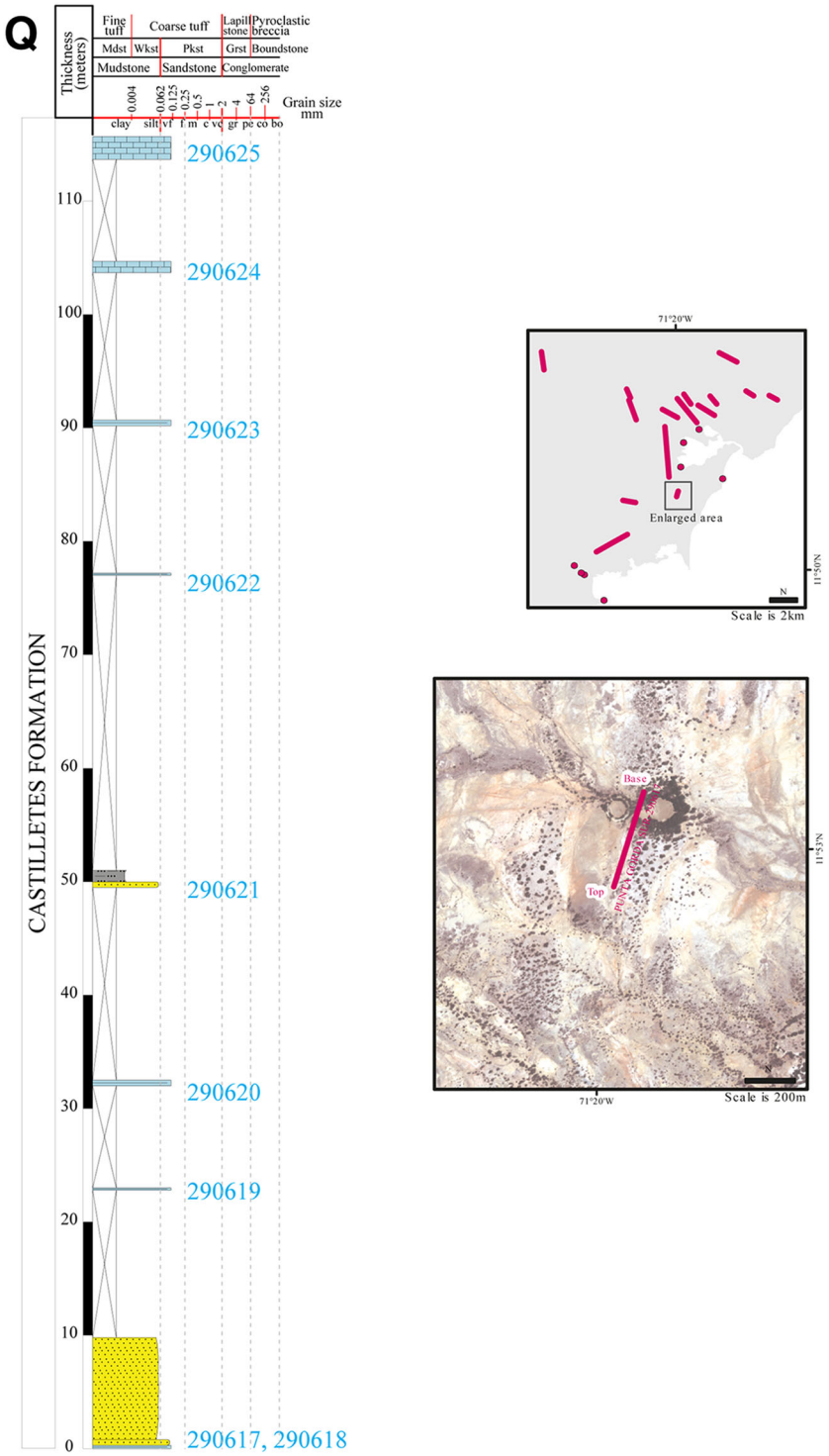
Age The invertebrate fauna of the Jimol Formation shares high similarity with the Cantaure Formation (latest Early Miocene) of Venezuela (Jung 1965) and the Culebra Formation (Early Miocene) of Panama (Woodring 1957).

Fig. 3 continued



Most notable among mollusks are frequent specimens of *Orthaulax*, a taxon that is widespread in the Caribbean during the Early Miocene and earliest Middle Miocene (Vokes and Vokes 1968). Other marine invertebrate taxa identified from the formation are regarded as indicative of the latest Early Miocene (e.g., "*Paraleptopecten*"

Fig. 3 continued



quirosensis, *Cyclinella venezuelana,* and *Conus* cf. *chipolanus*) or Middle Miocene (e.g., *Modulus tamenensis*), or are similar to Middle-Late Miocene forms (e.g., *Lindapecten* cf. *buchivacoanus*). On the basis of $^{87}Sr/^{86}Sr$ ratios, a mean age of 17.3 Ma (range of 16.89 ± 0.12 Ma–17.51 ± 0.11 month year) is calculated for beds northwest of the village of Paraguachón at the top of the formation (Table 2). A late Early Miocene (Burdigalian

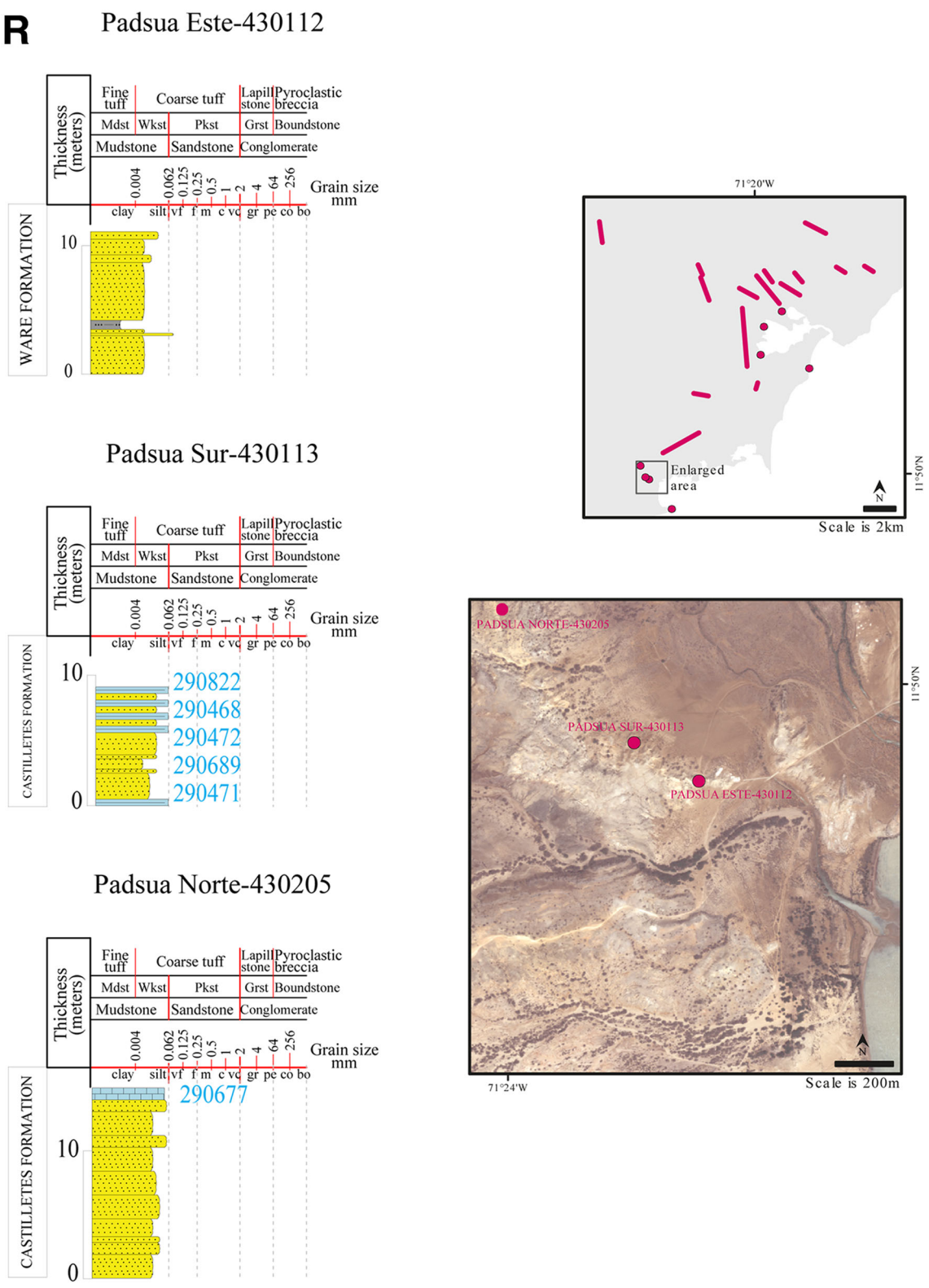


Fig. 3 continued

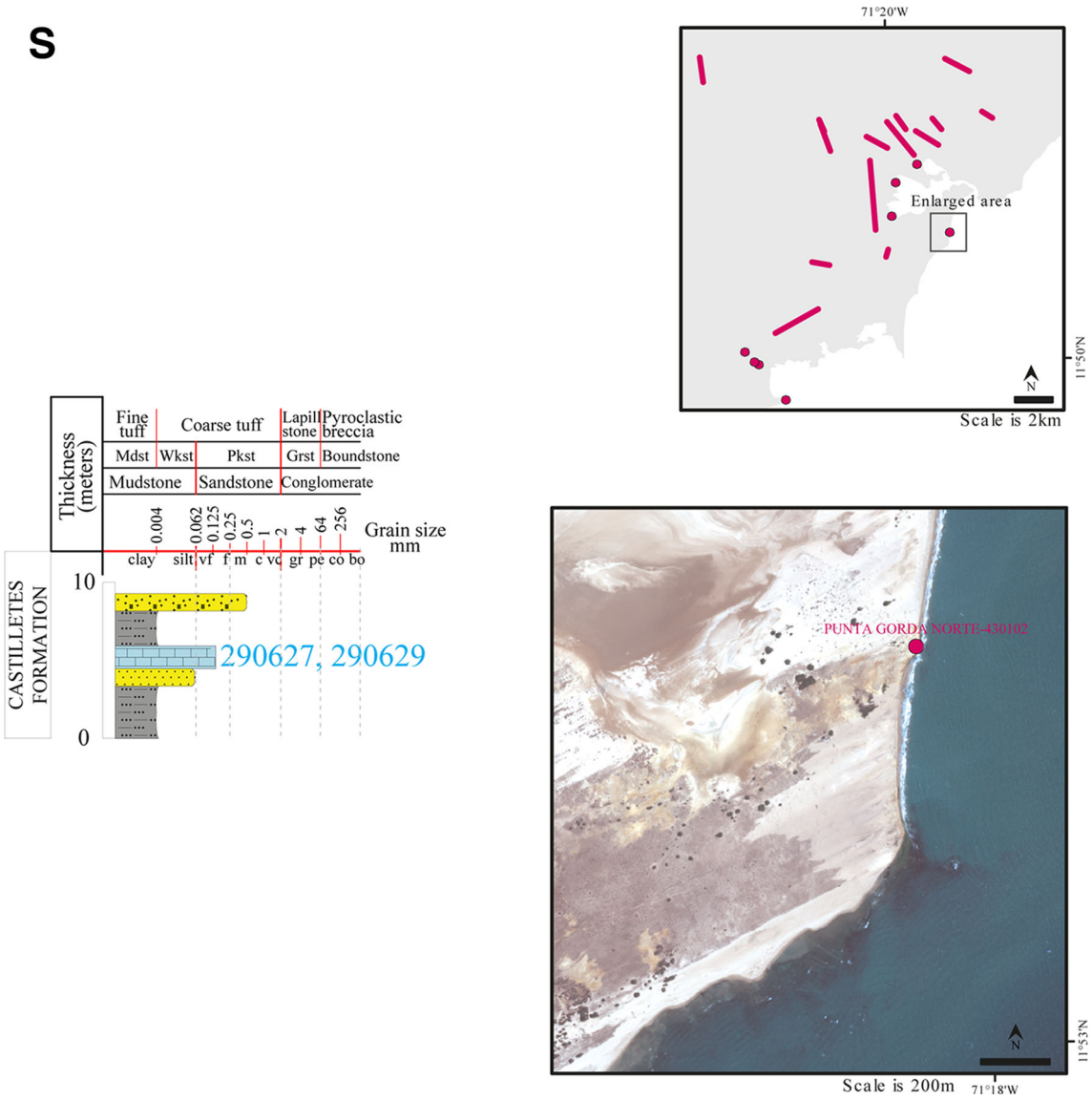


Fig. 3 continued

17.9–16.7 Ma) age is, therefore, assigned to the Jimol Formation on the basis of macroinvertebrate biostratigraphy and $^{87}Sr/^{86}Sr$ isotope chronostratigraphy (see also Hendy et al. (2015) in this issue).

Environment of deposition The Jimol Formation was deposited in a shallow marine environment, inner shelf depth (<50 m).

Correlations This unit is correlated with the upper Agua Clara Formation, lower Cerro Pelao Formation of Falcon Basin in Venezuela (Fig. 2). The formation is also correlative with the Cantaure Formation (ca. 18–17 Ma) of the Paraguaná Peninsula in Venezuela (Díaz de Gamero 1974; Rey 1996).

Castilletes formation

Here, we present a new definition for the Jimol Formation. Depositional environment interpretation will be presented in the following section.

Name The formation is named after the town of Castilletes, located in the Guajira Peninsula (Rollins 1965).

Lectostratotype The area between Patajau Valley and Makaraipao village in the central Cocinetas Basin (Figs. 4 and 7). Coordinates for the base and top of the composite stratigraphic section are 11.946800°N and 71.3321833°W, and 11.94896°N and 71.27136°W, respectively.

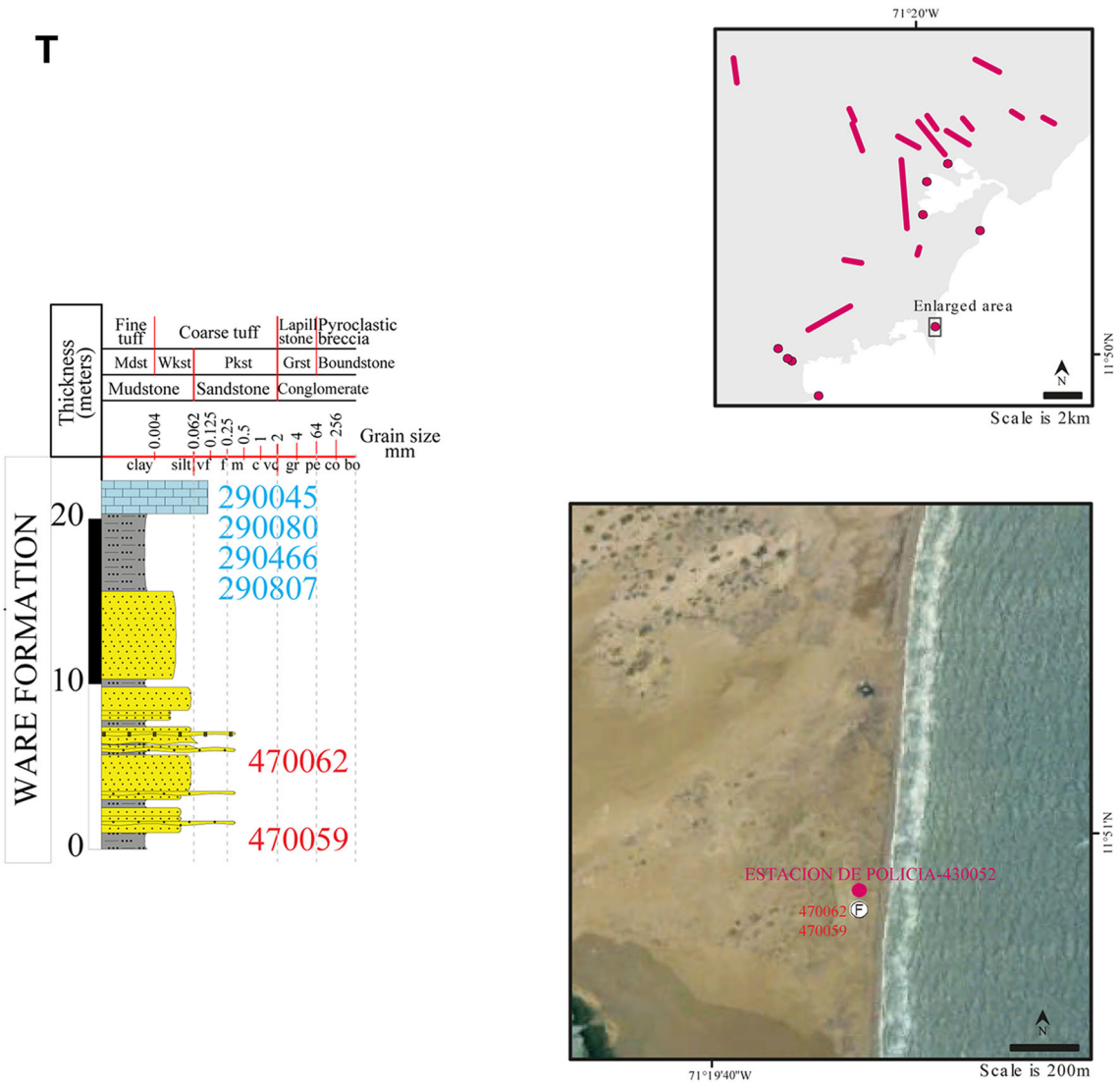


Fig. 3 continued

Description The formation is composed of gray massive mudstone, fossiliferous mudstone and siltstone, fossiliferous wackestone to packstone, and medium-grained to conglomeratic fossiliferous lithic to quartz sandstone. Thick successions of mudstone (~50 m) dominate the unit and form long valleys. Thin beds of biosparite and sandstone (50 cm–2 m) are interbedded and form laterally extensive ridges. Sandstone often present planar and cross-bedded stratification. Sandy and silty facies increase toward the top of the formation, forming prominent hills. Fossiliferous horizons are common within the unit, with marine invertebrate fossils occurring in a broad range of facies (calcareous, sandy, silty, and muddy sediments), whereas terrestrial vertebrates tend to be restricted to muddy sediments and are often associated with freshwater invertebrate fossils. Sandy facies toward the top of the formation are also rich in vertebrate fossils (Figs. 7, 8).

Lower and upper boundaries The lower boundary of the Castilletes Formation is defined by a hardground surface that overlies a distinctive fossiliferous wackestone cropping out along the northern edge of the Patajau Valley. This surface can be observed along strike in several parts of the Cocinetas Basin. The upper boundary is an angular unconformable contact with the overlying Ware Formation (Fig. 9). This contact frequently is eroded or not exposed, cropping out only at a few sites when erosional remnants of the Ware Formation are preserved.

Thickness and regional extent A total thickness of 440 m was measured in the lectostratotype. The Castilletes Formation crops out along the eastern margin of the Cocinetas

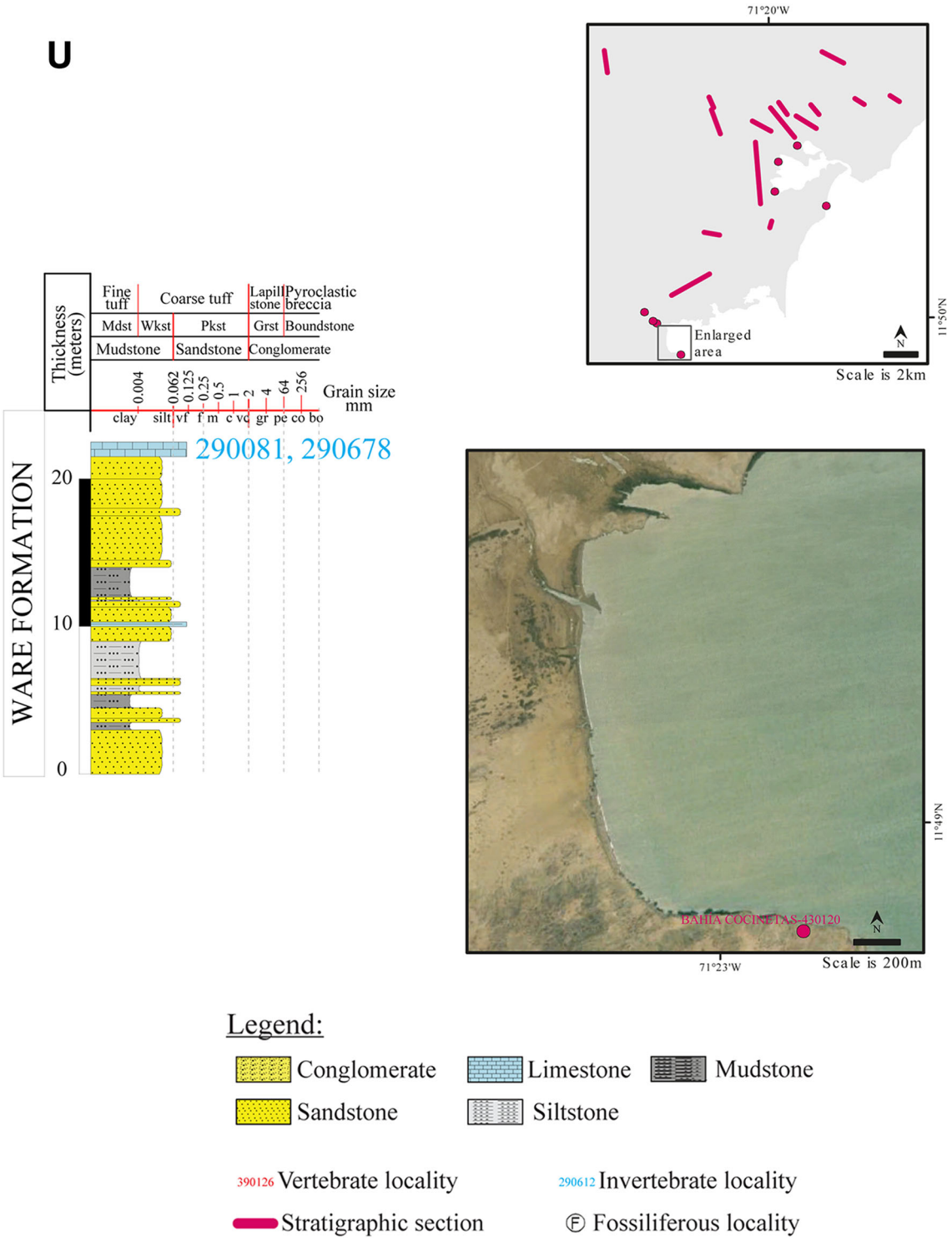


Fig. 3 continued

Basin, but correlative strata may occur farther north and south of the presently mapped area (Figs. 6 and 7).

Invertebrate palaeontology Dominant taxa of the Castilletes Formation include *Potamides, Turritella*, *Anadara (Cunearca)*, and *Pitar*. Other frequently occurring 'genera' include *Neverita (Glossaulax), Polinices*, *Melongena*, *Architectonica, Conus, Tucetona, Mytilus*, *Dallocardia*, and *Caryocorbula*. A total of 149 'species' of mollusks (82 gastropods, 66 bivalves, and 1 scaphopod), 3 echinoderms, and 4 arthropods have been identified from

Table 2 Strontium isotope data and age estimates from Cocinetas Basin, Colombia

Unit	Section	Height (m)	Sample	Taxon	$^{87}Sr/^{86}Sr$	Age (Ma)[a]	Range (Ma)[a]
Jimol	290432	35	17068	*Anadara guajiraensis*	0.7086413	17.33	16.96–17.65
Jimol	290432	35	17068	*Anadara guajiraensis*	0.7086331	17.45	17.10–17.75
Jimol	290432	66	16882	*Turritella matarucana*	0.7086293	17.51	17.16–17.80
Jimol	290432	66	16882	*Turritella matarucana*	0.7086679	16.89	16.48–17.27
Castilletes	430103	104	17049	*Crassostrea* sp.	0.7087012	16.31	15.93–16.71
Castilletes	430103	104	17049	*Anadara guajiraensis*	0.708706	16.22	15.85–16.62
Castilletes	430103	104	17073	*Crassostrea* sp.	0.7086964	16.33	16.01–16.80
Castilletes	430103	104	17073	*Phacoides* sp.	0.7087145	16.07	15.71–16.46
Castilletes	170514	98	16918	*Anadara guajiraensis*	0.708774	15.14	14.50–15.51
Castilletes	170514	98	16918	*Anadara guajiraensis*	0.708766	15.29	14.79–15.64
Castilletes	170514	98	16918	*Anadara guajiraensis*	0.708759	15.39	14.97–15.75
Castilletes	170514	98	16918	*Anadara guajiraensis*	0.708767	15.27	14.76–15.62
Castilletes	170514	99	16885	*Glyptoactis paraguana*	0.708756	15.43	15.04–15.79
Ware	430052	21	10347	*Crassostrea virginica*	0.7091014	1.57	1.22–2.24
Ware	430052	21	10347	*Crassostrea virginica*	0.7090591	3.28	2.12–4.99
Ware	430052	21	10347	*Plicatula gibbosa*	0.7090639	2.78	1.93–4.82
Ware	430052	21	10347	*Euvola codercola*	0.7090584	3.4	2.15–5.03
Ware	430120	22	16880	*Argopecten* sp.	0.7090104	5.71	5.09–6.10
Ware	430120	22	16880	*Plicatula gibbosa*	0.709058	3.4	2.15–5.03

[a] Ages from look-up tables in McArthur et al. (2001)

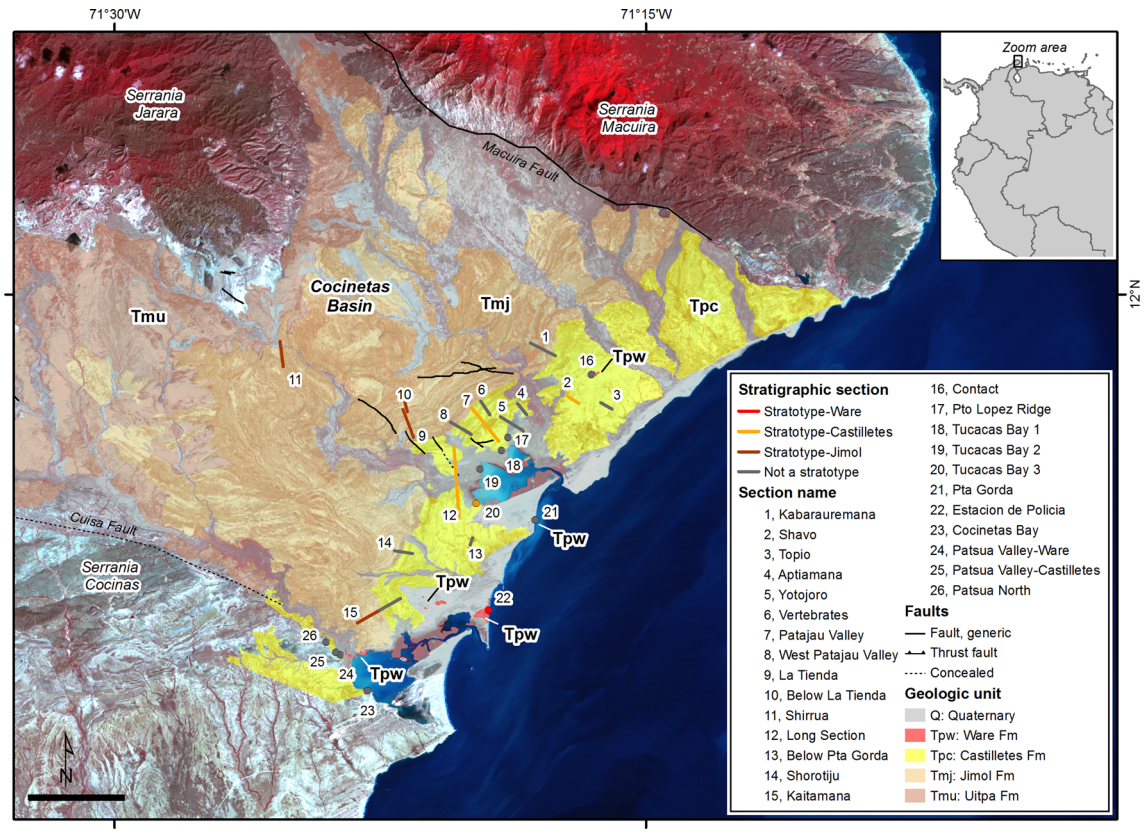


Fig. 4 Location of stratigraphic sections and stratotypes. Image from Landsat 8 OLI-TIRS sensor (January 10, 2014, RGB 432). Geologic units are shown in *transparent colors*. *Scale bar* is 5 km

Table 3 Stratigraphic sections measured and described in the Cocinetas Basin

Name	Locality ID	Start point Lat	Start point Long	End point Lat	End point Long	Units	Stratigraphic thickness (m)
Aptiamana	430169	11.94858	−71.3105	11.94331	−71.30615	Castilletes	120
Bahiá Cocinetas	430120	11.81326	−71.38096	NA	NA	Ware	23
Bahiá Tucacas medio	430116	11.91771	−71.32802	NA	NA	Castilletes	19
Bahiá Tucacas norte	430115	11.9264	−71.31784	NA	NA	Castilletes	19
Bahiá Tucacas sur	430117	11.90156	−71.32996	NA	NA	Castilletes	18
Estacion de Policia	430052	11.8512	−71.324	NA	NA	Ware	22
Kabarauremana	430214	11.97727	−71.30439	11.97115	−71.29266	Jimol	92
Kaitamana	430118	11.84519	−71.38591	11.85683	−71.36547	Jimol-Castilletes	159
La Tienda	290432	11.94568	−71.36437	11.93286	−71.35949	Jimol-Castilletes	66
Long	170514	11.92822	−71.34039	11.9261	−71.3594	Castilletes	150
Padsua este	430112	11.83023	−71.39391	NA	NA	Ware	12
Padsua norte	430205	11.83615	−71.40053	NA	NA	Castilletes	15
Padsua sur	430113	11.83142	−71.39599	NA	NA	Castilletes	9
Paraguachon	430121	11.950503	−71.36389	11.944578	−71.362183	Jimol	85
Patajau norte	430103	11.9468	−71.3321833	11.93099	−71.31923	Castilletes	198
Patajau sur	430105	11.93979	−71.34218	11.934167	−71.332139	Castilletes	113
Puerto Lopez sur-este	290609	11.93269	−71.31495	NA	NA	Castilletes	22
Punta Gorda norte	430102	11.89371	−71.30212	NA	NA	Castilletes-Ware?	9
Punta Gorda sur	290617	11.88535	−71.3316	11.881906	−71.332682	Castilletes	115
Shavo	430200	11.95189	−71.28664	11.94861	−71.28152	Castilletes	70
Shirrua	360182	11.9779	−71.42234	11.96593	−71.42068	Jimol	26
Shorotiju	430119	11.87934	−71.36836	11.877962	−71.35984	Jimol-Castilletes	128
Topio este	290825	11.94596	−71.2659	11.94896	−71.27136	Castilletes	107
Topio oeste	430170	11.962211	−71.275608	NA	NA	Castilletes-Ware	28
Vertebrates	170533	11.94982	−71.32783	11.94324	−71.32336	Castilletes	97
Yotojoro	430203	11.94238	−71.31844	11.93564	−71.30763	Castilletes	39

the unit (see Hendy et al. (2015), in this issue, for a detailed description of this assemblage).

Vertebrate paleontology The 18 most fossiliferous localities (Table 4) have yielded 572 vertebrate specimens including representatives of nine mammal 'orders' (Astrapotheria, Cetacea, Cingulata, Litopterna, Notoungulata, Pilosa, Rodentia, Sirenia, and Sprassodonta), three reptile 'orders' [Crocodilia, Testudines, and Squamata (Cadena and Jaramillo 2015)], and ten fish 'orders' (Pristiophoriformes, Orectolobiformes, Lamniformes, Carcharhiniformes, Rajiformes, Myliobatiformes, Characiformes, Siluriformes Antoine et al. (2013a), Perciformes, and Lepidosireniformes) (Tables 4, 5; Online Resource 2, Fig. 8).

Fossil flora Fossil wood fragments.

Age The invertebrate fauna of the Castilletes Formation is highly similar not only to that of the underlying Jimol Formation, but also to the Cantaure Formation (latest Early Miocene) of Venezuela. Numerous marine invertebrate taxa identified from the formation are latest Early Miocene (e.g., "*Paraleptopecten*" *quirosensis, Cyclinella venezuelana, Glyptoactis paraguanensis, Eupleura kugleri, Cymia cocoditana, Euclia werenfelsi*, *Conus* cf. *chipolanus,* and *Conus talis*), Middle Miocene (e.g., *Modulus tamenensis*), or Middle to Late Miocene (e.g., *Lindapecten* cf. *buchivacoanus*) in age. *Orthaulax* (see discussion for Jimol Formation) has not been recorded from the Castilletes Formation, consistent with its presently known last appearance during the earliest Middle Miocene. A mean age of 16.2 Ma (range of 16.33 ± 0.11 Ma–16.07 ± 0.10 month year) is calculated for beds in the Patajau Valley near the base of the formation, on the basis of $^{87}Sr/^{86}Sr$ ratios. Beds in the middle part of the formation near Makaraipao yielded a mean $^{87}Sr/^{86}Sr$ ratio-derived age of 15.30 Ma (range of 15.14 ± 0.13 Ma–15.43 ± 0.09 (Table 2). No strontium isotope ratio age estimates have yet been established for the uppermost part of the formation. A late Early Miocene to early Middle Miocene (upper Burdigalian-Langhian, 16.7–14.2 Ma) age is assigned to the Castilletes Formation on the basis of macroinvertebrate biostratigraphy and

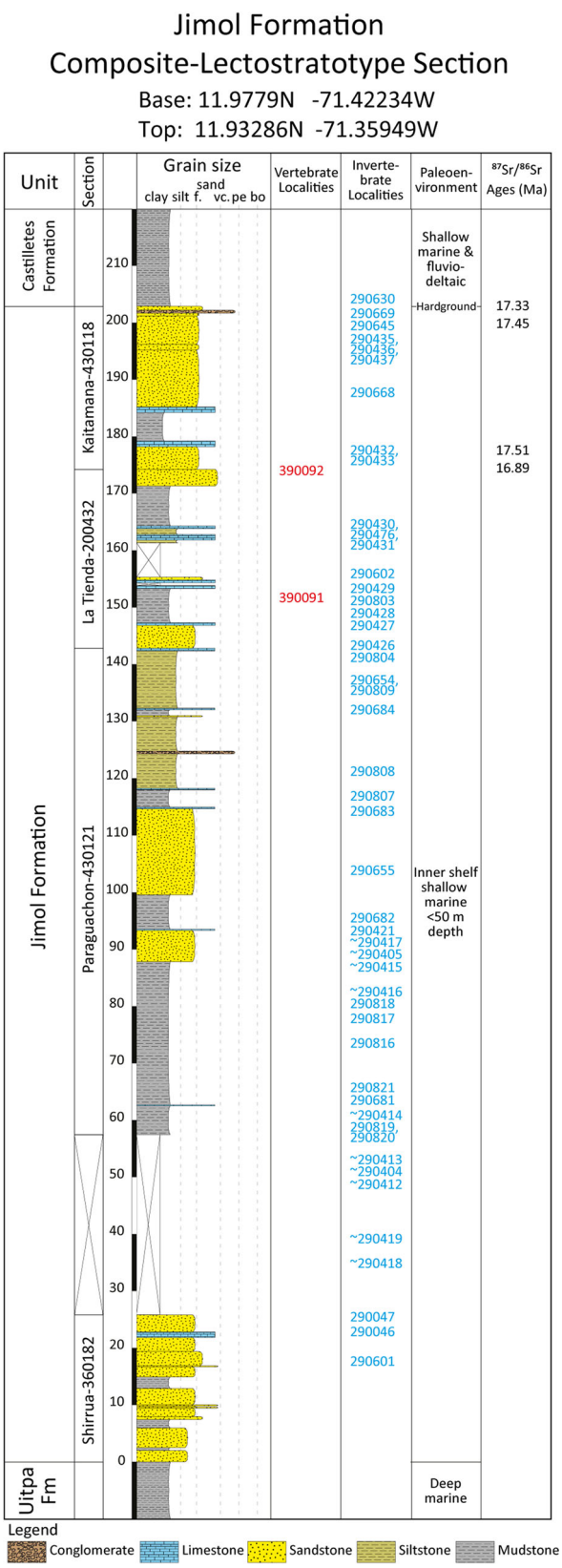


Fig. 5 Jimol Formation composite lecto-stratotype. Geographic location of the individual sections can be found in Figs. 3 and 4

$^{87}Sr/^{86}Sr$ isotope chronostratigraphy (see also Hendy et al. (2015), in this issue).

Environment of deposition The Castilletes Formation was deposited in a shallow marine (estuarine, lagoonal, and shallow subtidal) to fluvio-deltaic environment with strong fluvial influence.

Correlations The Castilletes Formation correlates with the upper Cerro Pelado Formation (17.5–17 Ma sensu Quiroz and Jaramillo 2010) and Querales Formation (17–14.5 Ma sensu Quiroz and Jaramillo 2010) of the Falcon Basin in Venezuela (Fig. 2). This unit is also correlative with the Cantaure Formation (ca. 18–17 Ma) of the Paraguaná Peninsula in Venezuela.

Ware formation

Here, we introduce the Ware Formation (new), provide a formal definition, and an interpretation of depositional environments.

Name The formation is named after the wayuunnaiki (language of the indigenous Wayuu people on the Guajira Peninsula) term meaning "friend". Because the stratotype of the Ware Formation crops out along the border between Colombia and Venezuela, its name pays tribute to the friendship between both countries.

Stratotype The stratotype of the Ware Formation crops out in the hills located at the northernmost point of the Colombia-Venezuela border at 11.8512°N and 71.324°W (Figs. 4, 8, 10).

Description The formation is composed of grayish yellow fine lithic to quartz sandstone and muddy lithic to quartz sandstone, light gray mudstone, reddish gray pebbly conglomerate with sedimentary and metamorphic rock fragments, yellowish gray fossiliferous packstone, and sandy to conglomeratic beds with high fossil content. Lenticular conglomerates with sedimentary and metamorphic rock fragments, very rich in vertebrate fossils, dominate the base of the sequence; they are interbedded with mudstone, sandy mudstone, and fossiliferous fine grained lithic to quartz sandstone with planar bedding (~7 m). Thick levels of fine lithic to quartz sandstone and sandy mudstone with cross- and planar bedding, and metric clinoforms compose the middle part of the sequence (~15 m). The uppermost horizon of the Ware comprises fossiliferous packstone with gravel-size fragments that vary laterally from packstone to sandy conglomerate (~3 m) (Fig. 10).

Lower and upper boundaries The lower boundary is an angular unconformable contact with the underlying Castilletes Formation; this boundary is exposed in sections Patsua Sur-Este-430113 and Topio Oeste—430170

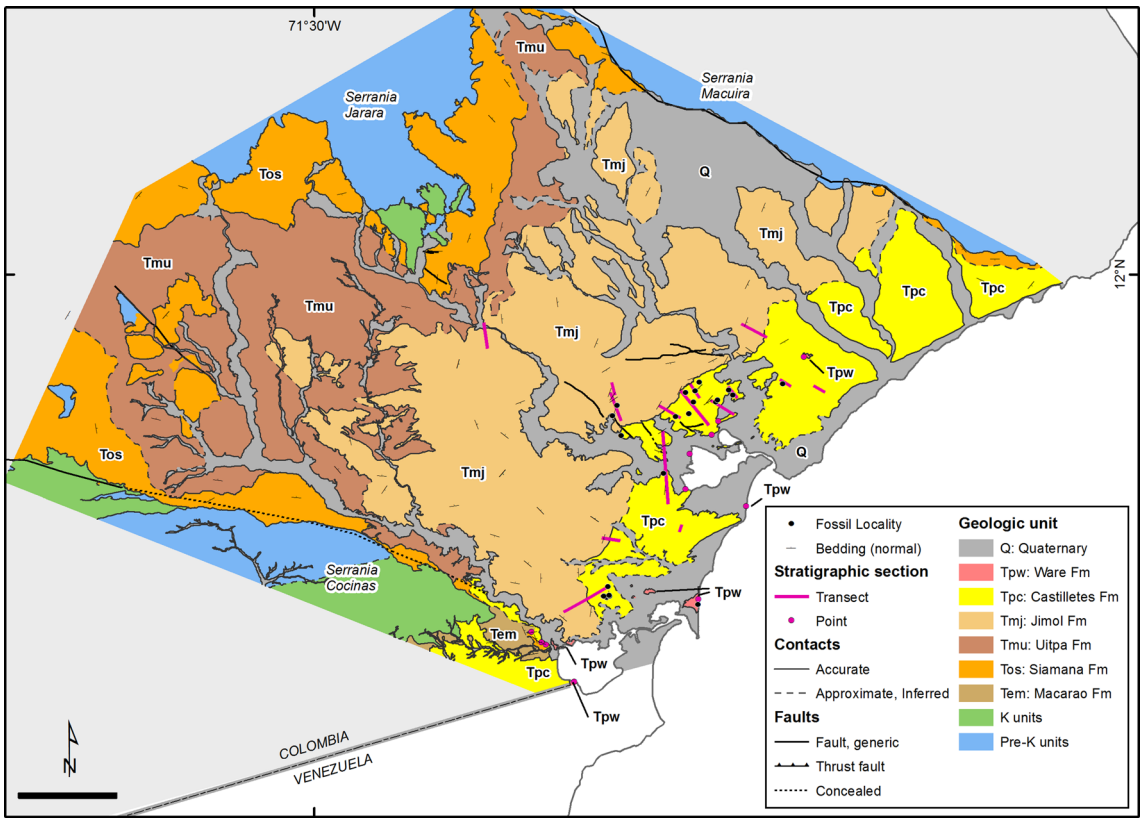


Fig. 6 Geologic map of Cocinetas Basin. Figure includes location of stratigraphic sections measured and described in this work. *Scale bar* is 5 km

(Figs. 3m, v and 9). This contact frequently is eroded or not exposed, cropping out only at few sites. The upper boundary is a fossiliferous packstone in the stratotype, which varies laterally to conglomeratic packstone and pebbly conglomerate. This layer marks the youngest preserved Neogene sedimentation in the Cocinetas Basin.

Thickness and Regional Extent: The total thickness of the stratotype is 25 m, but the formation is also mapped from small hills of apparently correlative strata distributed randomly along the eastern portion of Cocinetas Basin (Figs. 6 and 10).

Invertebrate paleontology The marine invertebrate assemblage of the Ware Formation is quite distinct relative to underlying units. Notably, the assemblage comprises a completely dissolved (moldic) aragonite fauna, whereas the shells of the calcitic forms (pectinids, ostreids) are generally well preserved as shells. Calcitic taxa such as *Argopecten, Euvola*, *Nodipecten*, *Crassostrea, Plicatula*, and *Spondylus*, and large moldic specimens of aragonitic *Anodontia* and *Codakia* are particularly distinctive in the unit. Other common moldic 'genera' with aragonitic shells include *Bulla, Laevicardium, Trachycardium*, and *Macrocallista.* More than 50 'species' of mollusks (18 gastropods and 38 bivalves), and one echinoderm have thus far been identified from the formation (see Hendy et al. (2015), in this issue, for a detailed description of this assemblage).

Vertebrate paleontology Three localities have yielded 708 specimens documenting seven mammal 'orders' (Artiodactyla, Carnivora, Cingulata, Litopterna, Notoungulata, Pilosa, and Rodentia), two reptile 'orders' (Crocodilia, Testudines), and six fish 'orders' (Carcharhiniformes, Rajiformes, Myliobatiformes, Characiformes, Perciformes, and Siluriformes Antoine et al. (2013b) (Tables 4, 5; Online Resource 2, Fig. 8).

Fossil flora Fossil wood fragments.

Age The marine invertebrate fauna of the Ware Formation shows a greater similarity with modern assemblages offshore of the Guajira Peninsula than with those of the underlying units. Few taxa provide finely resolved age constraints for the Ware Formation. Pectinids such as *Amusium mortoni* (Early Pliocene to earliest Pleistocene), *Euvola codercola* (latest Miocene to Pliocene), and *Nodipecten arnoldi* (Late Pliocene to Early Pleistocene) suggest an age close to the Pliocene–Pleistocene boundary. A number of internal molds of a shell similar to *Acrosterigma dalli* (Heilprin 1887) were also collected. *Acrosterigma dalli* is known only from the earliest Pleistocene of Florida and is not easily confused with other cardiid bivalves. A mean age

Table 4 Major vertebrate fossiliferous localities for the Jimol, Castilletes, and Ware formations

ID	Latitude	Longitude	Strat section ID	Strat section name	Formation	Stratigraphic meter
130023	11.9361	−71.3284	430103	Patajau Norte	Castilletes	78
130024	11.9348	−71.3344	430103	Patajau Sur	Castilletes	80
130025	11.9498	−71.2853	430200	Shavo	Castilletes	21
150166	11.852	−71.3661	430118	Kaitamana	Castilletes	73
150167	11.9469	−71.3101	430169	Aiptiamana	Castilletes	23
290632	11.9458	−71.3299	430103	Patajau Norte	Castilletes	28
340071	11.9447	−71.3083	430203	Yotojoro	Castilletes	26
340072	11.9413	−71.3161	430203	Yotojoro	Castilletes	10
390090	11.9261	−71.3594	430103	La Tienda	Castilletes	72
390091	11.9399	−71.3614	290432	La Tienda	Jimol	11
390092	11.9351	−71.3634	290432	La Tienda	Jimol	35
390093	11.9089	−71.3401	170514	Long	Castilletes	128
390094	11.9465	−71.3255	430103	Vertebrates	Castilletes	46
390126	11.8525	−71.3676	430118	Kaitamana	Castilletes	83
430053	11.8512	−71.3241	430118	Kaitamana	Castilletes	97
430202	11.8568	−71.3655	430118	Kaitamana	Castilletes	150
470058	11.9506	−71.3237	430103	Patajau Norte	Castilletes	28
470059	11.8487	−71.3243	430052	Estación de Policia	Ware	2
470062	11.8487	−71.3243	430052	Estación de Policia	Ware	5
470065	11.9261	−71.3594	430103	La Tienda	Castillets	69
470066	11.9465	−71.3255	430103	Patajau Norte	Castilletes	45
490006	11.9423	−71.3152	430203	Yotojoro	Castilletes	17

of 3.2 Ma (range of 3.40 Ma to 2.78 Ma) is calculated for the shell bed at the top of the formation from $^{87}Sr/^{86}Sr$ ratios (Table 2). A Late Pliocene (Piacenzian) age is assigned to the Ware Formation on the basis of macroinvertebrate biostratigraphy and $^{87}Sr/^{86}Sr$ isotope chronostratigraphy.

Environment of deposition The base of the Ware Formation was deposited in a fluvio-deltaic environment, whereas the marine invertebrate assemblage at the top of the unit contains taxa typical of exposed open-ocean shoreface and nearshore settings, but with proximity to coral reef habitats.

Correlations: The Ware Formation correlates with the San Gregorio Formation (ca. 4–2 Ma sensu Quiroz and Jaramillo 2010) in the Falcon Basin in Venezuela (Fig. 2).

Discussion

Stratigraphy

We propose three major changes to the previous stratigraphy of Cocinetas Basin: (1) a new definition for the Jimol-Castilletes formational boundary, (2) a new definition of the upper boundary of the Castilletes Formation, and therefore, a new definition of both the Jimol and Castilletes Formations, and (3) a new Pliocene lithostratigraphic unit, the Ware Formation.

The upper boundary of the Jimol Formation was defined by Rollins (1965) as the limit between a sandy claystone at the top of Jimol and an oyster-bearing limestone at the base of the Castilletes. However, oyster-bearing limestones are laterally discontinuous and common both at the top of the Jimol and throughout the lower Castilletes sensu Rollins (see sections 360182, 290432 and 430121 in Fig. 3a–c). Therefore, they are not a good criterion for a boundary. The contact between the Jimol and Castilletes Formations is very transitional, and detailed stratigraphy shows a gradual environmental change between the two units (Figs. 5, 6, and 7, Online Resource 1). The Jimol Formation is dominated by coarse detritic and calcareous lithologies with fewer interbedded muddy levels. In contrast, the Castilletes Formation is dominated by mudstones with fewer interbedded, thin, calcareous, and coarse detritic levels that form ridges in the landscape. We propose this facies change as the new limit between these units, with a conspicuous and laterally extensive hardground surface at the top of a transgressive calcareous layer as the boundary surface between the two formations (sections 290432, 430214, 430118, 430119, 430103, and 170533 in Fig. 3b, d–f, h and i).

Table 5 Major groups of vertebrate taxa identified from the jimol, castilletes and ware formations

Class	Order	Family	Jimol	Castilletes	Ware
Mammalia	Artiodactyla	Camelidae			×
Mammalia	Astrapotheria	Astrapotheriidae		×	
Mammalia	Carnivora	Procyonidae			×
Mammalia	Cetacea	Odontoceti		×	
Mammalia	Cetacea	Mysticeti		×	
Mammalia	Cingulata	Glyptodontidae		×	×
Mammalia	Cingulata	Pampatheriidae		×	×
Mammalia	Litopterna	Macraucheniidae		×	
Mammalia	Litopterna	Proterotheriidae		×	×
Mammalia	Notoungulata	Leontinidae		×	
Mammalia	Notoungulata	Toxodontidae		×	×
Mammalia	Notoungulata	Interatheriidae		×	
Mammalia	Pilosa	Megalonychidae			×
Mammalia	Pilosa	Megatheriidae		×	×
Mammalia	Pilosa	Mylodontidae			×
Mammalia	Rodentia	Caviidae			×
Mammalia	Rodentia	Dinomyidae		×	
Mammalia	Rodentia	Erethizontidae			×
Mammalia	Rodentia	Hydrochoeridae			×
Mammalia	Sirenia			×	
Mammalia	Sparassodonta			×	
Reptilia	Crocodilia	Alligatoridae		×	×
Reptilia	Crocodilia	Crocodylidae	×	×	×
Reptilia	Crocodilia	Gavialidae	×	×	
Reptilia	Squamata	Boidae		×	
Reptilia	Testudines	Podocnemididae		×	×
Reptilia	Testudines	Chelidae		×	
Aves				×	×
Actinopterygii	Characiformes	Characidae		×	×
Actinopterygii	Characiformes	Cynodontidae			×
Actinopterygii	Characiformes	Serrasalmidae		×	×
Actinopterygii	Perciformes	Cichlidae			×
Actinopterygii	Perciformes	Sciaenidae		×	×
Actinopterygii	Perciformes	Sparidae		×	
Actinopterygii	Perciformes	Sphyraenidae		×	
Actinopterygii	Siluriformes	Ariidae		×	
Actinopterygii	Siluriformes	Callichthyidae		×	
Actinopterygii	Siluriformes	Doradidae		×	×
Actinopterygii	Siluriformes	Pimelodidae		×	×
Chondrichthyes	Carcharhiniformes	Carcharhinidae	×	×	×
Chondrichthyes	Carcharhiniformes	Hemigaleidae	×	×	
Chondrichthyes	Carcharhiniformes	Sphyrnidae		×	×
Chondrichthyes	Lamniformes	Lamnidae	×	×	
Chondrichthyes	Lamniformes	Otodontidae		×	
Chondrichthyes	Myliobatiformes	Dasyatidae		×	
Chondrichthyes	Myliobatiformes	Myliobatidae	×	×	×
Chondrichthyes	Myliobatiformes	Rhinopteridae		×	
Chondrichthyes	Orectolobiformes	Ginglymostomatidae		×	

Table 5 continued

Class	Order	Family	Jimol	Castilletes	Ware
Chondrichthyes	Pristiophoriformes	Pristiophoridae		×	
Chondrichthyes	Rajiformes	Pristidae		×	×
Chondrichthyes	Rajiformes	Rhynchobatidae		×	
Chondrichthyes	Rajiformes	Rhynobatidae		×	
Chondrichthyes	Squaliformes	Dalatiidae	×		
Sarcopterygii	Lepidosireniformes	Lepidosirenidae		×	

In addition, we propose a new lithostratigraphic unit based on field observations and $^{87}Sr/^{86}Sr$ geochronological results, which reveal a large unconformity within the upper portion of the Castilletes Formation of Rollins (1965). This unconformity encompasses a gap in the sedimentary record between 14.5 and 3.5 Ma. We redefine the Castilletes Formation and propose the new Ware Formation as the sub-horizontal fluvio-deltaic to shallow marine deposits overlying this angular unconformity. Ware deposits are distributed along the eastern margin of the Cocinetas Basin, cropping out as isolated hills with sub-horizontal strata, which are essentially remnants of what would have been a widely distributed unit (Fig. 6).

Paleoenvironments

The Jimol Formation accumulated in a shallow marine environment although it expresses the overprint of rapid oscillations of relative sea level. Intervals of marine flooding led to deposition of wackestone to packstone biosparites with diverse shallow marine invertebrate communities, including thick oyster banks. Periods of lowered relative sea level are dominated by coarse calcareous and lithic sandstone with cross- and planar bedding deposited in shore-face environments and massive mudstone deposited in foreshore to backshore environments. The Castilletes Formation also exhibits these depositional sequences, but in a more proximal setting, marking the transition to a fluvio-deltaic dominated environment. Transgressive intervals are dominated by coquina, oyster banks, and shore-face deposits, whereas regressive intervals are characterized by muddy facies of estuarine and fluvio-deltaic plain settings and sandy facies that represent deltaic channels. The vertebrate fossil assemblage of the Castilletes Formation is dominated by large crocodiles, large turtles, and grazing and browsing herbivores, which suggests the presence of year-round fresh-water bodies including rivers, swamps, and lakes as well as grasslands and forests up to 14.5 Ma. The Ware Formation is dominated by sandstone and muddy sandstone, mudstone, pebbly conglomerate, and packstone to conglomeratic packstone lithologies indicating a fluvio-deltaic environment. Its extensive vertebrate fossil record, including crocodiles, turtles, and grazing and browsing herbivores, also suggests the existence of year-round bodies of fresh water, much like those in the Castilletes Formation. These deposits and their associated fauna are in stark contrast to modern environments of the Cocinetas Basin, which are extremely dry, with a prolonged dry season (~11 months), dominated by xerophytic vegetation and lacking large rivers or year-round bodies of fresh water. This contrast suggests that a major change in the landscape occurred over the past 2.5–3 m.y., leading to the extant aridification of the region (Fig. 8).

Great american biotic interchange (GABI)

Despite important advances in the Neogene Neotropical paleontology, the Neotropical vertebrate fossil record is still scarce when compared with temperate regions (Carrillo et al. 2014; MacFadden 2006a). There are only five well-studied faunal associations in the Neogene of the Neotropics (Fig. 10) although it is a vast territory (twice the area of continental Europe) with high levels of biodiversity. Sites include the Early Miocene terrestrial deposits of the Panamanian isthmus (MacFadden 2006a, b, 2009, 2010; MacFadden and Higgins 2004; Rincon et al. 2012; Whitmore Stewart 1965); the Middle Miocene deposits from La Venta (Kay et al. 1997); the Late Miocene vertebrate deposits from Acre (Cozzuol, 2006; Frailey 1986; Negri et al. 2010; Ribeiro et al. 2013), the Early to Late Miocene deposits in the Peruvian Amazon (Antoine et al. 2007, 2013; Marivaux et al. 2012; Negri et al. 2010; Tejada-Lara et al. 2014), and the Late Miocene (~6–10 Ma) and Pliocene (2–4 Ma) deposits of the Urumaco sequence, in particular the Urumaco, Codore, and San Gregorio Formations in north western Venezuela (e.g., Aguilera 2004; Aguilera and Rodriguez de Aguilera 2001; Forasiepi et al. 2014; Head et al. 2006; Linares 2004; Quiroz and Jaramillo 2010; Sánchez-Villagra and Aguilera 2006; Sánchez-Villagra et al. 2003; Sánchez-Villagra 2006; Sánchez-Villagra and Clack 2004; Vucetich et al. 2010; Winkler and Sánchez-Villagra 2006) (Fig. 10).

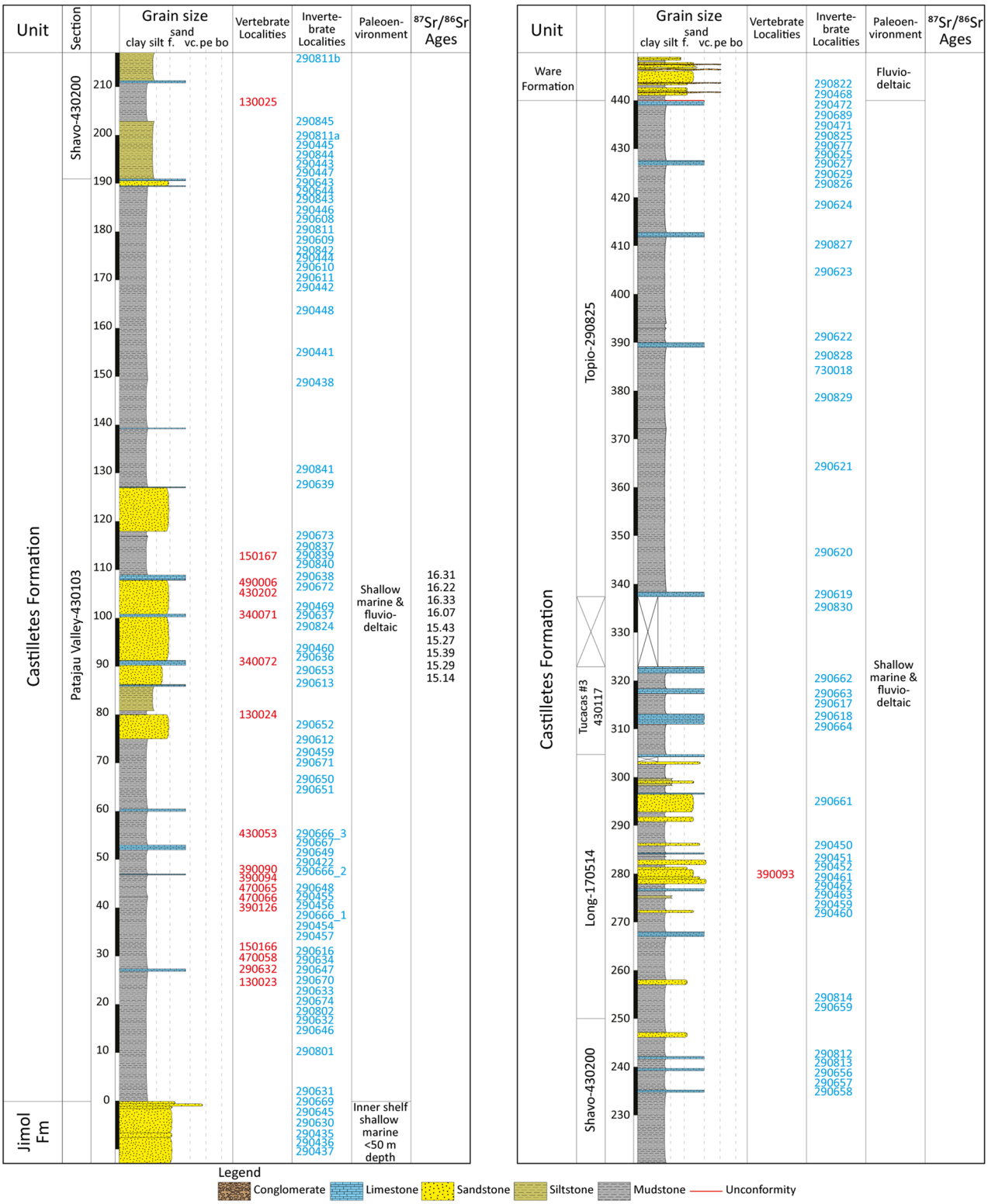
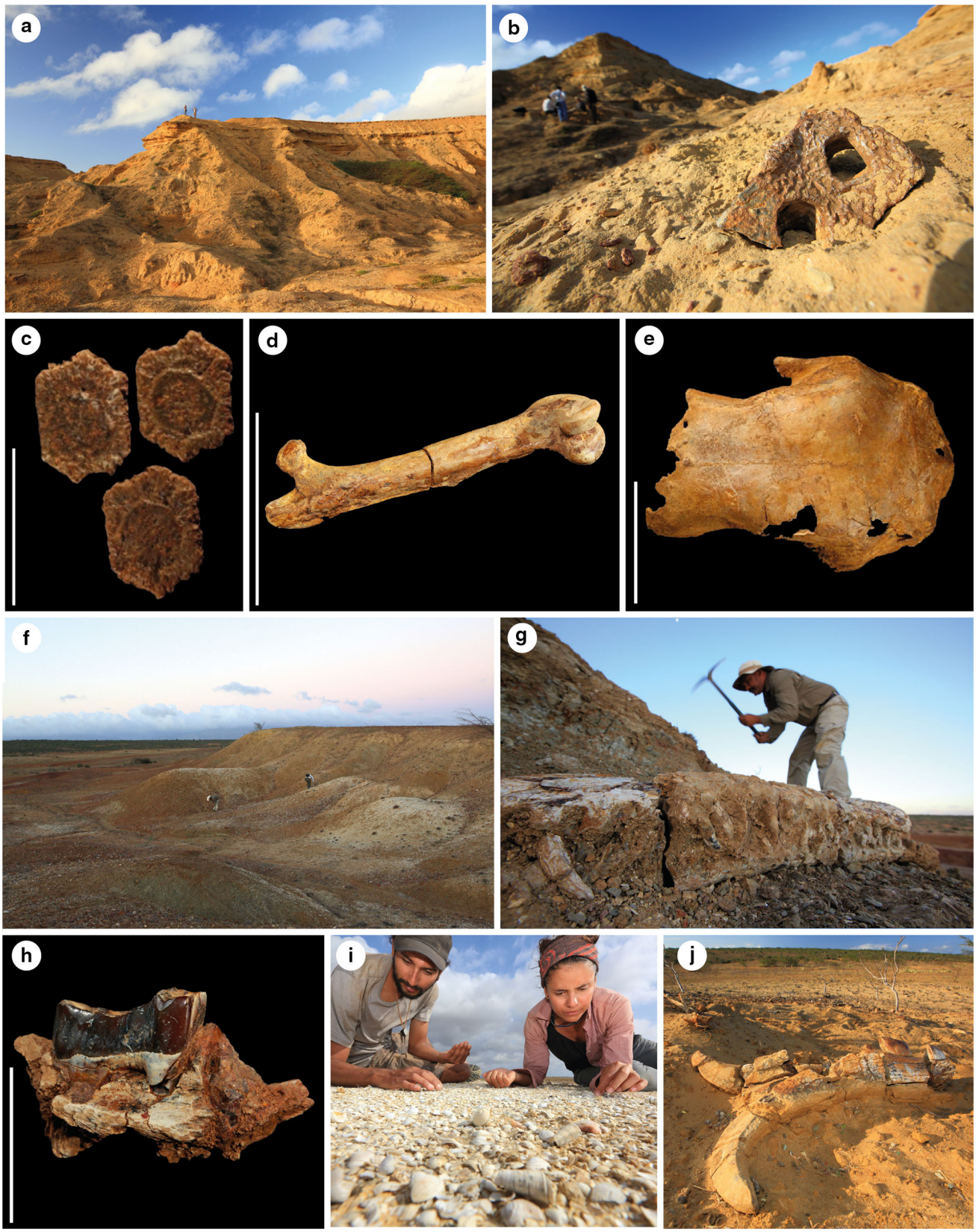


Fig. 7 Castilletes Formation composite lecto-stratotype. Geographic location of the individual sections can be found in Figs. 3 and 4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◀**Fig. 8** Main fossiliferous localities and representative fossils from the Ware and Castilletes formations. (**a**–**e**) Ware Formation; **a** Locality 470062; photograph shows the characteristic subhorizontal position of the Ware Formation beds; this site correspond to the stratotype section of the Ware Formation mainly composed by conglomerates at the base, sandstones, and muddy sandstones in the middle, and a thick fossiliferous packstone level at the *top*; (**b**) braincase of Crocodylidae (STRI-ID34591); (**c**) Glyptodontidae osteoderms (STRI-ID12928), *scale bar* 5 cm; (**d**) Hydrochoeridae femur (STRI-ID34315), *scale bar* 10 cm; and (**e**) Megalonychidae skull (STRI-ID12924), *scale bar* 10 cm. (**f**–**j**) Castilletes Formation; (**f**) Locality 390094, typical valley and ridge topography of Castilletes Formation formed by the thick muddy levels with hard calcareous and sandy levels on top; (**g**) Gavialidae rostrum (STRI-ID34540); (**h**) Leontinidae lower molar (STRI-ID34312), *scale bar* 5 cm; (**i**) fossiliferous mudstone covered with gastropods; (**j**) Locality 470058 with a mandible of Astrapotheriidae (STRI-ID34383). Photographs taken by Christian Ziegler (**a**–**j**)

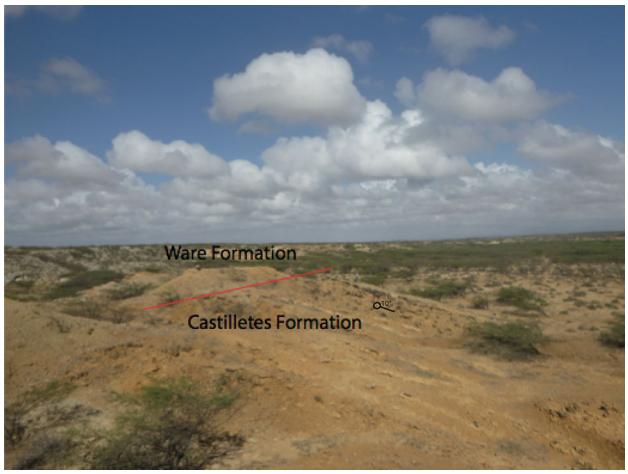

Fig. 9 Angular unconformity between the Castilletes and Ware formations (11.83142°N and 71.39599°W)

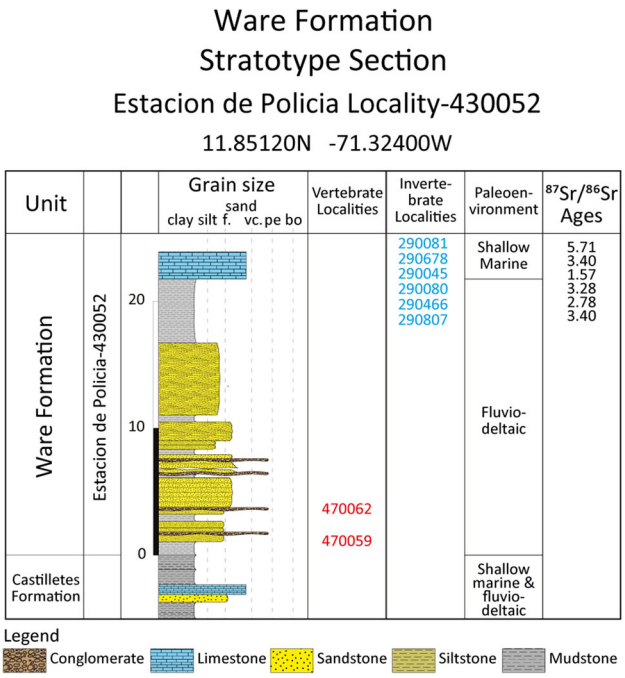

Fig. 10 Ware Formation Stratotype. Geographic location of the individual sections can be found in Fig. 3 and Online Resource 1

The late Neogene witnessed one of the largest biogeographic events in Earth's history, the Great American Biotic Interchange (GABI). This episode of species dispersal between the previously disconnected landmasses of South America and Central-North America was the product of the complex rise of the isthmus of Panama, which started ca. 10–12 Ma (Jaramillo et al. 2013; Montes et al. 2012; Sepulchre et al. 2014) and culminated with the full rise of the isthmus ca. 3.5 Ma (Coates et al. 2003, 2004). There is an extensive record of publications on GABI over many decades (Leigh et al. 2014; Marshall et al. 1982; Stehli and Webb 1985; Verzi and Montalvo 2008; Wallace 1876; Webb 1976, 1985, 1991, 2006; Woodburne 2010). However, the fossil record of South America that has been used to understand GABI has been mostly from temperate parts of the continent (Argentina, Chile, and Bolivia) (Carrillo et al. 2014). Furthermore, the biochronology that is applied throughout South America, known as South American Land Mammal Ages (SALMAs), is largely based on these temperate regions (Fig. 10). The timing and dynamics of GABI, however, cannot be fully understood without the inclusion of the tropical region, because the point of connection between the two landmasses was within the tropics (Fig. 11).

A detailed study of the rich terrestrial fossil record preserved in the Cocinetas Basin will serve to fill two major gaps. First, the assemblages of the Early–Middle Miocene of the Jimol and Castilletes Formations are similar in age to geographically proximal Panamanian faunas that lived on the other side of the seaway on Central American landmasses. These Panamanian assemblages already had a mixture of North American-derived taxa, mostly mammals (MacFadden 2006a, b, 2009, 2010; MacFadden et al. 2012; MacFadden and Higgins 2004; Rincon et al. 2012, 2013; Slaughter 1981; Whitmore and Stewart 1965) and South American-derived taxa, mostly crocodiles, turtles, snakes, and plants (Cadena et al. 2012; Hastings et al. 2013; Head et al. 2012; Jaramillo et al. 2014). Furthermore, the Jimol and Castilletes Formations record span the full range of the Middle Miocene climatic optimum (Zachos et al. 2001), the last event of major warming during the Cenozoic. Analyses of the terrestrial and aquatic vertebrate paleoecology and the palynology of these units will contribute to our understanding of how tropical ecosystems respond to global warming.

Second, the fossil record of the Ware Formation is of particular interest because it constitutes the most proximal sequence in both time (Late Pliocene) and space (600 km away) to the Panamanian isthmus and its final rise at

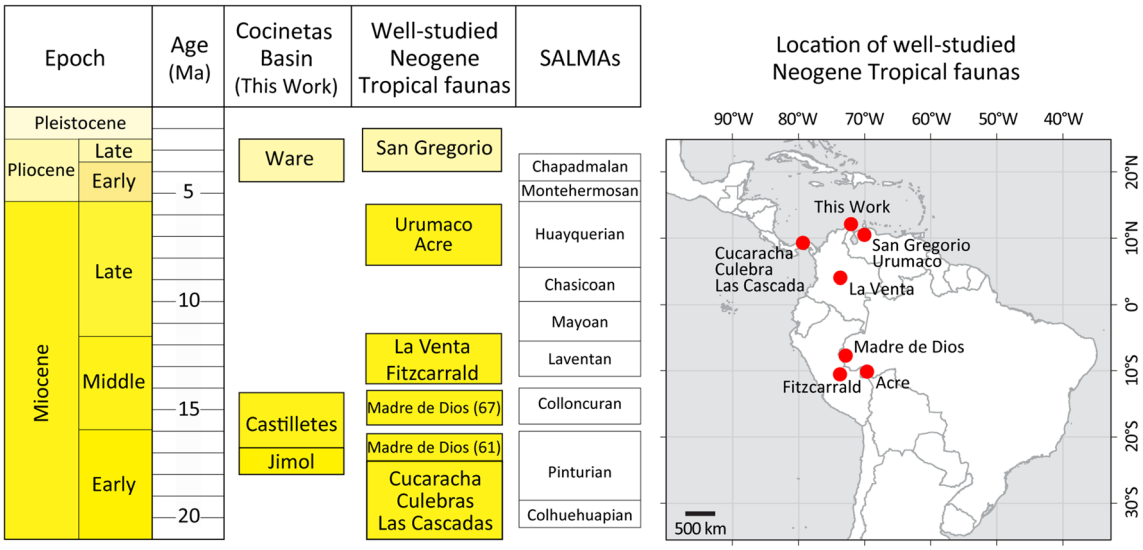

Fig. 11 Temporal and geographic distribution of the only well-studied Neogene vertebrate localities within the Neotropical region

3.5 Ma. Together with the San Gregorio Formation in western Venezuela (Vucetich et al. 2010; Castro et al. 2014; Forasiepi et al. 2014), it will provide a window into the most critical interval in GABI's history, the Late Pliocene (Woodburne 2010).

Conclusions

The Jimol, Castilletes, and Ware Formations record the paleoenvironmental transition of the Cocinetas Basin from a shallow marine shelf to a fluvio-deltaic system. New stratigraphic and geochronological data result in a revised definition of the Neogene lithostratigraphic units in the Cocinetas Basin. The geologic record shows the Neogene in Cocinetas Basin as a shallow marine to fluvio-deltaic system characterized by successive transgressions and regressions. This geological reconnaissance has also highlighted tremendously diverse and important fossil assemblages throughout the Jimol, Castilletes, and Ware Formations. These new fossil data are of great value for paleobiogeographic, paleogeographic, paleoceanographic, and paleoenvironmental interpretations. The faunal and floral fossil record of the Cocinetas Basin indicates a humid ecosystem during the Neogene and reveals that drastic climate change that occurred during the past two to three million years.

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